TN-961

Part IV

Technical Note N-961

CORROSION OF MATERIALS IN HYDROSPACE

PART IV - COPPER AND COPPER ALLOYS

BY

Fred M. Reinhart

April 1968

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NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California

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CORROSION OF MATERIALS IN HYDROSPACE

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Y-F015-21-05-001

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ABSTRACT

A total of 1050 specimens of 46 different copper alloys were exposed at two depths, 2,500 and 6,000 feet, in the Pacific Ocean for periods of time varying from 123 to 1064 days in order to determine the effects of deep ocean environments on their corrosion resistance.

Corrosion rates, types of corrosion, pit depths, stress corrosion cracking resistance, changes in mechanical properties and analyses of corrosion products of the alloys are presented.

Copper, beryllium-copper, arsenical admiralty brass, aluminum brass, nickel brass, G bronze, modified G bronze, M bronze, leaded tin bronze, phosphorous bronze A, phosphorous bronze D, nickel-aluminum bronzes, Ni-Vee bronze A, Ni-Vee bronze B, Ni-Vee bronze C, copper-nickel alloys 95-5, 80-20, 70-30 containing 0.5 percent iron, 70-30 containing 5 percent iron, 55-45, nickel-silver containing 18 percent nickel, and Cu-Ni-Zn-Pb corroded uniformly and their corrosion rates were low, 1 MPY or less after 1 year at a depth of 2,500 feet and after 2 years at a depth of 6,000 feet.

The remainder of the alloys were attacked by selective corrosion: commercial bronze, red brass, yellow brass, Muntz metal, Naval brass, manganese bronze, nickel-manganese bronze, wrought 5 and 7 percent aluminum bronzes, cast 10, 11 and 13 percent aluminum bronzes, 3 percent silicon bronze and silicon bronze A.

The copper alloys were not susceptible to stress corrosion cracking.

Only the mechanical properties of the alloys attacked by selective corrosion were adversely affected.

The corrosion products consisted of cupric chloride, copper hydroxide-chloride, metallic copper, copper oxy-chloride and nickel hydroxide.

The aggressiveness of the sea water and of the bottom sediments on the copper alloys was about the same except for the copper-nickel alloys where the bottom sediments were less aggressive.

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PREFACE

The U. S. Naval Civil Engineering Laboratory is conducting a research program to determine the effects of deep ocean environments on materials. It is expected that this research will establish the best materials to be used in deep ocean construction.

A Submersible Test Unit (STU) was designed, on which many test specimens can be mounted. The STU can be lowered to the ocean floor and left for long periods of exposure.

Thus far, exposures have been made at two deep-ocean test sites and at a surface sea water site in the Pacific Ocean. Six STUs have been exposed and recovered. Test Site I (nominal depth of 6,000 feet) is approximately 81 nautical miles west-southwest of Port Hueneme, California, latitude 33°44'N and longitude 120°45'W. Test Site II (nominal depth of 2,500 feet) is 75 nautical miles west of Port Hueneme, California, latitude 34°06'N and longitude 120°42'W. A surface sea water exposure site (V) was established at Point Mugu, California (34°06'N - 119°07'W) to obtain surface immersion data for comparison purposes.

This report presents the results of the evaluations of copper and copper alloys exposed at the above three test sites.

INTRODUCTION

The development of deep diving vehicles which can stay submerged for long periods of time has focused attention on the deep ocean as an operating environment. This has created a need for information concerning the behavior of common materials of construction as well as newly developed materials with promising potentials, at depths in the ocean.

To study the problems of construction in the deep ocean, project "Deep Ocean Studies" was established. Fundamental to the design, construction and operation of structures, and their related facilities is information with regard to the deterioration of materials in deep ocean environments. This report is devoted to the portion of the project concerned with determining the effects of these environments on the corrosion of metals and alloys.

The test sites for the deep ocean exposures are shown in Figure 1 and their specific geographical locations are given in Table 1. The complete oceanographic data at these sites, obtained from NCEL cruises between 1961 and 1967, are summarized in Figure 2. Initially, it was decided to utilize the site at the 6,000 foot depth. Because of the minimum oxygen concentration zone found between the 2,000 and 3,000 foot depths, during the early oceanographic cruises, it was decided to establish a second exposure site (STU II-1 and II-2) at a nominal depth of 2,500 feet. For comparative purposes, the surface water site V was established. Even though the actual depths are shown in the tables, the nominal depths of 6,000 and 2,500 feet are used throughout the text.

A summary of the characteristics of the bottom waters 10 feet above the bottom sediments at the two deep ocean exposure sites and at the surface exposure site is given in Table 1.

Sources of information pertaining to the biological characteristics of the bottom sediments, biological deterioration of materials, detailed oceanographic data, and construction, emplacement and retrieval of STU structures are given in Reference 1.

The procedures for the preparation of the specimens for exposure and for evaluating them after exposure are described in Reference 2.

Previous reports pertaining to the performance of materials in the deep ocean environments are given in References 1 through 8.

This report is a discussion of the results obtained of the corrosion of copper and copper alloys for the seven exposure periods shown in Table 1.

RESULTS AND DISCUSSIONS

The results presented and discussed herein also include the corrosion data for copper alloys exposed on the STU structures for the

International Nickel Company, Incorporated. Permission for their incorporation in this report has been granted by Dr. T. P. May, Manager, Harbor Island (Kure Beach) Corrosion Laboratory, Wrightsville Beach, North Carolina, Reference 9.

Results from other participants in the NCEL exposures are also included; Annapolis Division, Naval Ship Research and Development Center (formerly Marine Engineering Laboratory) (Reference 10) and the Chemistry Division, NCEL, (Reference 11).

Deep ocean corrosion results from the Atlantic Ocean (References 12 and 13), surface corrosion data from the Atlantic Ocean (Reference 14) and surface corrosion data from the Pacific Ocean (References 15 and 16) are included for comparison purposes.

COPPER

The chemical composition of the coppers are given in Table 2, their corrosion rates and types of corrosion in Table 3, their resistance to stress corrosion cracking in Table 4, and changes in their mechanical properties due to corrosion in Table 5.

Corrosion

The excellent corrosion resistance of copper is partially due to its being a relatively noble metal. However, in many environments its satisfactory performance depends on the formation of adherent, relatively thin films of corrosion products. In sea water corrosion, resistance depends on the presence of a surface oxide film through which oxygen must diffuse in order for corrosion to continue. This oxide film adjoining the metal is cuprous oxide covered with a mixture of cupric oxy-chloride, cupric hydroxide, basic cupric carbonate and calcium sulfate. Since oxygen must diffuse through this film for corrosion to occur it would be expected that under normal circumstances the corrosion rate would decrease with increase in time of exposure.

The corrosion rates of copper in sea water, both at depth and at the surface, are given in Table 2 and shown in Figure 3. The corrosion rate decreased with increase in duration of exposure at the 6,000 foot depth in the Pacific Ocean and the data from all three participants, Naval Civil Engineering Laboratory, International Nickel Company, Inc. and Naval Ship Research and Development Center was in very good agreement. At the 5,600 foot depth in the Atlantic Ocean, Reference 12, the corrosion rate for copper after 1050 days of exposure was practically the same as at the 6,000 foot depth in the Pacific Ocean. This close agreement of the corrosion rates of copper in the two oceans is not unexpected since the corrosion of copper is not appreciably affected by changes in oxygen concentration.

At depths of 4,250 and 4,500 feet in the Atlantic Ocean, Reference

13, the corrosion rates were about one-half the corrosion rate at 5,600 feet in the Atlantic Ocean and about two-thirds the corrosion rate at 6,000 feet in the Pacific Ocean. They were more in agreement with the NCEL corrosion rates of copper at the 2,500 foot depth in the Pacific Ocean.

At the 2,500 foot depth, the corrosion rates of copper as reported by INCO, Reference 9, were the same as those at 6,000 feet. However, the NCEL corrosion rates at the 2,500 foot depth were lower than those at the 6,000 foot depth. In both cases the corrosion rates were practically constant with increasing time of exposure.

The corrosion rate of copper was nearly constant with increasing time of exposure at the surface in the Atlantic Ocean at Kure Beach, North Carolina, Reference 14, but decreased with time of exposure at the surface in the Pacific Ocean at the Panama Canal Zone, Reference 16, and became constant with time after about 4 years of exposure.

At Port Hueneme Harbor in the Pacific Ocean, Reference 15, copper corroded at a constant rate over a two year period of exposure.

For practical purposes the corrosion of copper can be considered constant and of the same magnitude after exposure for 1 year in sea water at the surface and at depths in both the Atlantic and Pacific Oceans. The corrosion rates ranged between 0.5 and 1.5 MPY with an average of about 1 MPY.

Copper partially embedded in the bottom sediments at the 6,000 foot depth corroded at essentially the same rate as in the sea water at this depth as shown in Figure 4. The corrosion rate decreased with increasing duration of exposure. At the 2,500 foot depth copper corroded at a lower rate in the bottom sediment than in the sediment at the 6,000 foot depth as well as in the water at 2,500 feet.

The addition of about two percent beryllium to copper did not affect the corrosion of copper after 402 days of exposure at a depth of 2,500 feet. The beryllium-copper was in the form of wrought sheet and cast chain. Their corrosion rates were 0.6 and 0.5 MPY, respectively, in sea water and 0.5 and 0.5 MPY, respectively, in the bottom sediments while those of copper were 0.6 and 0.2 MPY in sea water and in the bottom sediment, respectively, Table 3. The corrosion of the wrought beryllium-copper sheet was not affected by welding either by the MIG or TIG processes.

Stress Corrosion

Oxygen free copper was not susceptible to stress corrosion cracking at stresses equivalent to 75 percent of its yield strength at a nominal depth of 2,500 feet for periods of exposure to 402 days as shown in Table 4.

Mechanical Properties

The effect of exposure on the mechanical properties of the coppers is shown in Table 5. The mechanical properties of oxygen-free copper and not welded and welded beryllium-copper, by both the MIG and TIG processes were not significantly affected by exposure in sea water at nominal depths of 2,500 and 6,000 feet.

COPPER-ZINC ALLOYS (BRASSES)

The chemical compositions of the copper-zinc alloys (brasses) are given in Table 6, their corrosion rates and types of corrosion in Table 7, their resistance to stress corrosion cracking in Table 8, and the effect of exposure in the sea water on their mechanical properties in Table 9.

Corrosion

Corrosion of the copper-zinc alloys usually occurs as uniform, pitting, crevice, dezincification or stress corrosion cracking. The tendency for the copper-zinc alloys to corrode by dezincification and stress corrosion cracking varies with the zinc content; the higher the zinc content of the alloy the greater the susceptibility. Pitting and crevice corrosion are usually caused by differential aeration cells.

Dezincification is the selective corrosion of copper-zinc alloys (brasses) by which the original alloy is converted into a spongy mass of copper which has poor mechanical strength. The most favored theory of this mechanism is that the metal corrodes as an alloy and the copper is subsequently redeposited.

Because it is not possible to remove all the corrosion products (redeposited, spongy copper) it is not possible to obtain true weight losses from which to calculate corrosion rates. Therefore, corrosion rates so obtained are always lower than they are actually. Hence, corrosion rates determined for dezincified copper-zinc alloys are not reliable for assessing the corrosion of such alloys.

The corrosion rates of the copper-zinc alloys are shown graphically in Figures 5 through 16.

The corrosion rates of commercial bronze, shown in Figure 5, were constant with duration of exposure through 751 days of exposure in the sea water at the 6,000 foot depth and decreased slightly thereafter. The corrosion rates in sea water at the 2,500 foot depth were lower than those at the 6,000 foot depth and decreased with increasing duration of exposure. However, in the bottom sediments at the 6,000 foot depth the corrosion rates increased with duration of exposure while those at the 2,500 foot depth decreased with increasing duration of exposure and they were lower than those at the 6,000 foot depth. The corrosion rates of commercial bronze at both depths, both in the sea water and in the bottom sediments were lower than those at the surface of the Pacific Ocean, at NCEL and at Fort Amador, Panama Canal Zone, Reference 16, as shown in Figure 5.

The commercial bronze was slightly dezincified after 402 days of exposure both in the sea water and in the bottom sediment at a depth of 2,500 feet. It was also reported to have dezincified at the surface in the Pacific Ocean at Fort Amador, Panama Canal Zone, Reference 16.

For all practical purposes the corrosion rates of commercial bronze both in sea water and in the bottom sediments at the 6,000 foot and 2,500 foot depths can be considered constant with increasing time of exposure. The corrosion rates at both depths were less than at the surface and the rate at the 2,500 foot depth was slightly less than that at the 6,000 foot depth.

The corrosion rate of red brass, Figure 6, was the same in the bottom sediments as in sea water at the 6,000 foot depth and decreased with increasing time of exposure. However, at the 2,500 foot depth, red brass corroded at a much slower rate in the bottom sediments than in the sea water and the corrosion rates decreased as the duration of exposure was increased.

After about 400 days of exposure, red brass corroded at about the same rate at the surface at Harbor Island, North Carolina in the Atlantic Ocean, Reference 10, as it did at 2,500 feet in the Pacific Ocean. At the surface in the Pacific Ocean it corroded at about the same rate as at the 6,000 foot depth.

Red brass was slightly dezincified, the first evidence of which was found after 123 days of exposure in the bottom sediment at a depth of 6,000 feet, Table 7.

In general, red brass corroded less at the 2,500 foot depth than at the 6,000 foot depth and the corrosion rates at both depths decreased as the time of exposure increased.

Yellow brass, Figure 7, also corroded at the same rate in the bottom sediments as in the sea water at the 6,000 foot depth and they decreased asymptotically with time. At the 2,500 foot depth, yellow brass corroded less in the bottom sediments than in the sea water and the rates were nearly constant with increasing time of exposure. At a depth of 4,250 feet in the Atlantic Ocean, Reference 13, the corrosion rate of yellow brass increased with time of exposure and after 200 days of exposure was the same as at a depth of 2,500 in the Pacific Ocean. There was slight to moderate dezincification of yellow brass after 751 and 1064 days of exposure in the sea water at the 6,000 foot depth, Table 7. After 181 days of exposure at the surface in the Pacific Ocean, yellow brass corroded at a higher rate than at the 6,000 foot depth and was slightly dezincified.

Arsenical Admiralty, Figure 8, like yellow brass, corroded at the same rate in the bottom sediments as in sea water at the 6,000 foot depth and the rate decreased asymptotically with time. At the 2,500 foot depth it corroded at essentially the same rate in sea water as at the 6,000 foot depth. In the bottom sediments at the 2,500 foot depth arsenical admiralty corroded at a lower rate than in the sea water. The corrosion rate of arsenical admiralty increased with time of exposure at a depth of 4,250 feet in the Atlantic Ocean, Reference 13, and after 200 days of exposure the corrosion rate was the same as at the 6,000 foot depth in the Pacific Ocean. The absence of any dezincification of arsenical admiralty is attributed to the slight amount of arsenic added to this alloy. It corroded at a higher rate at the surface in the Pacific Ocean than at depth as shown in Figure 8.

The corrosion of Muntz Metal at the 6,000 foot depth was erratic as shown in Figure 9. This is attributed to the dezincification of the alloy. The corrosion rates at the 2,500 foot depth were essentially constant with time and those in the bottom sediments were lower than those in the sea water. Muntz metal corroded at a higher rate at the surface in the Pacific Ocean than at either depth and at the Panama Canal Zone. Even though Muntz metal was dezincified during exposure at the surface in the Pacific Ocean, Fort Amador, Panama Canal Zone, Reference 16, its corrosion rate decreased asymptotically with time and was lower than at the 6,000 foot depth. Muntz metal suffered from dezincification at the surface and at both depths in the Pacific Ocean, the extent varying from slight to severe. The severity of the dezincification after 751 days of exposure at a depth of 6,000 feet is shown in Figure 10, the thickness of the specimen was reduced by 28 percent. The dark bands on the edges are dezincified areas.

Naval brass, Figure 11, corroded at a slower rate in sea water at the 6,000 foot depth in the Pacific Ocean than at a depth of 5,600 feet in the Atlantic Ocean, Reference 12, at the surface in the Pacific Ocean at Fort Amador, Panama Canal Zone, Reference 16, and at Port Hueneme Harbor, California, Reference 15. However, after 1050 days of exposure at 5,600 feet in the Atlantic Ocean and 1064 days of exposure at 6,000 feet in the Pacific Ocean the corrosion rates of Naval brass were essentially the same. The corrosion rates at both surface locations and at the 6,000 foot depth decreased and became asymptotic with time even though the rates were different. The differences in the rates can be attributed at least partially to differences in the temperatures at the three sites. The Naval brass was reported to have been dezincified at the Panama Canal Zone but no dezincification was reported at the surface at Port Hueneme or at depth in the Atlantic and Pacific Oceans. Dezincification could be an additional cause (in addition to temperature) for the higher corrosion rate at the Panama Canal Zone.

Manganese bronze, Figure 12, behaved similarly to Muntz metal, Figure 9, in that it corroded erratically at the 6,000 foot depth which is attributed to dezincification. At the 2,500 foot depth, the corrosion rates decreased slightly with increasing time of exposure and in the bottom sediment were lower than in the sea water. The corrosion rate of manganese bronze at the surface of the Pacific Ocean at NCEL was considerably higher than at either depth as well as at other locations. It was also severely dezincified. The corrosion rate of manganese bronze decreased asymptotically with time at the surface in the Pacific Ocean, Fort Amador, Panama Canal Zone, Reference 16, and was constant with time between one and two and a half years of exposure in

Port Hueneme Harbor, California, Reference 15; it was lower at the latter site. The corrosion rates at the 6,000 foot depth, both in sea water and in the bottom sediments, were comparable with that at the surface in the Pacific at the Panama Canal Zone. The corrosion rate of manganese bronze at the surface in the Pacific Ocean at Port Hueneme Harbor, California, Reference 15, was comparable with that in sea water at the 2,500 foot depth, both were lower than at the 6,000 foot depth and at the Panama Canal Zone. There was negligible corrosion of manganese bronze in the bottom sediments at the 2,500 foot depth. The manganese bronzes were attacked to a considerable extent by dezincification except that no dezincification was reported for the manganese bronze in Port Hueneme Harbor.

Cast nickel-manganese bronze was severely attacked by dezincification after 402 days of exposure, both in the sea water and in the bottom sediments, at a depth of 2,500 feet and after 751 days of exposure in sea water at a depth of 6,000 feet, Figure 13. The corrosion rate of the cast nickel-manganese bronze at the surface in the Pacific Ocean was much less than at either depth. The extent of the dezincification after 751 days of exposure at a depth of 6,000 feet is shown in Figure 14. The light area on the cross sections depicts the dezincification which is approximately 65 percent of the thickness of the specimen.

The corrosion rate of aluminum brass decreased gradually with increasing time of exposure in the sea water at the 6,000 foot depth, Figure 15. After 181 days of exposure at the surface in the Pacific Ocean, the corrosion rate was the same as in sea water at the 6,000 foot depth. In the bottom sediments at the 6,000 foot depth, the corrosion rates also decreased with increasing time of exposure to 751 days, then increased sharply between 751 days and 1064 days. At the 2,500 foot depth the corrosion rate in sea water also decreased with increasing time of exposure but in the bottom sediments it increased slightly. However, after 400 days of exposure the corrosion rates were the same in sea water and the bottom sediments at the 2,500 foot depth and in the bottom sediment at the 6,000 foot depth. At the 4,250 foot depth in the Atlantic Ocean, Reference 13, the corrosion rate of aluminum brass decreased slightly with time and was about the same as that in the bottom sediments at the 6,000 foot depth.

As shown in Figure 16, the corrosion rates of nickel brass decreased gradually with increasing time of exposure at both depths (2,500 and 6,000 feet) except in the sediments at the 2,500 foot depth where the alloy was practically uncorroded. Nickel brass corroded at slower rates in the bottom sediments at both depths than in the sea water and at slower rates at the 2,500 foot depth than at the 6,000 foot depth. It corroded at the surface in the Pacific Ocean at the same rate as in the sediment at the 6,000 foot depth.

There was one exception to the corrosion behavior which was common to all the copper-zinc alloys; their corrosion rates in the bottom sediment after 403 days of exposure were much lower than those after other times of exposure at the 6,000 foot depth, Table 7 and Figures 5, 6, 7, 8, 9, 12, 15 and 16. These low corrosion rates are attributed to a rather passive sediment at this location; i.e., very little if any sulfate reducing bacteria. This assumption is substantiated by the large population of wood borers and the presence of many deep-sea sponges found at the water-sediment interface which require oxygen to live and reproduce.

The performance of the copper-zinc alloys in sea water at the 2,500 and 6,000 foot depths is summarized in Figure 17 and in the bottom sediments at these depths in Figure 18.

Except for Muntz metal and manganese bronze the corrosion rates for the copper-zinc alloys at the 6,000 foot depth decreased with increasing time of exposure and could be encompassed within a rather narrow band as shown in Figure 17. The width of the band decreased from 1.2 MPY after 123 days of exposure to 0.6 MPY after 1064 days of exposure. The dotted curve within this band is for copper for comparison purposes; showing that after 1064 days of exposure the copper-zinc alloys corrode at rates which are within ± 0.3 MPY of that of copper. The curves above this band are for Muntz metal and manganese bronze both of which were dezincified to considerable degrees. Two other points, both for nickel-manganese bronze, were outside this band and are attributed to dezincification. The band encompassing the corrosion rates for the copper-zinc alloys at the 2,500 foot depth indicate that, in general, they were constant with time and were lower than the corrosion rate for copper. These bands also show that the corrosion rates of the copper-zinc alloys in sea water at depths of 2,500 feet and 6,000 feet were comparable, except for Muntz metal and manganese bronze.

Most of the corrosion rates for the copper-zinc alloys in the bottom sediments at the 6,000 foot depth can be conveniently encompassed within a band whose width is about 1.2 MPY after 123 days of exposure which narrows to 0.5 MPY after 1064 days of exposure as shown in Figure 18. The average corrosion rates decrease from 1.0 MPY after 123 days of exposure to 0.6 MPY after 1064 days of exposure. The dotted corrosion rate curve for copper bisects this band with the copper-zinc alloy corrosion rates being slightly higher than that for copper after 1064 days of exposure. The curve above the band is for manganese bronze which suffered considerable dezincification. The other points outside this band are for manganese bronze and nickel-manganese bronze which also were dezincified. The small band for the alloys in the bottom sediments at the 2,500 foot depth shows quite clearly that in addition to the corrosion rates being low, they were essentially constant with time.

A comparison of the bands for the copper-zinc alloys at the 6,000 foot depth shows that after 1064 days of exposure they were corroding at essentially the same rates in sea water and in the bottom sediments. However, at the 2,500 foot depth the corrosion rates in sea water were higher than those in the bottom sediments.

Stress Corrosion

Two copper-zinc alloys, arsenical admiralty and Muntz metal were exposed while stressed at values equivalent to 50 and 75 percent of their respective yield strengths, as shown in Table 8. They were immune to stress corrosion cracking for 403 days of exposure at a depth of 6,000 feet and 402 days of exposure at a depth of 2,500 feet.

Mechanical Properties

The effect of corrosion on the mechanical properties of three copper-zinc alloys, arsenical admiralty, Muntz metal and nickel-manganese bronze are given in Table 9 and shown graphically in Figures 19, 20, and 21.

The mechanical properties of arsenical admiralty were not impaired, Figure 19, while those of Muntz metal, Figure 20, and nickel-manganese bronze, Figure 21, were impaired. In both alloys, the impairment increased with time of exposure at both depths, 2,500 and 6,000 feet. The degree of impairment in both cases roughly paralleled the severity of the dezincification.

Corrosion Products

The corrosion products which formed on cast nickel-manganese bronze during 403 days of exposure at a depth of 6,000 feet were analyzed by X-ray diffraction, spectrographic, Infra-red spectrophotometer and quantitative analyses methods. The corrosion products were composed of cupric chloride ($CuCl_2 \cdot 2H_2O$); copper hydroxychloride ($Cu_2(OH)_3Cl$); copper as metal 35.98%; minor amounts of aluminum, iron, silicon, and sodium; chloride ions as Cl, 0.91%; sulfate ions as SO_4, 11.53%; small quantities of an organic compound or compounds present due to decomposed algae and vegetative materials.

BRONZES

The chemical compositions of the bronzes are given in Table 10, their corrosion rates and types of corrosion in Table 11, their resistance to stress corrosion cracking in Table 12 and the effect of exposure in the sea water on their mechanical properties in Table 13.

Corrosion

The corrosion rates of G bronze and modified G bronze are shown in Figure 22. At the 6,000 foot depth, from 123 to 1064 days of exposure, they corroded at essentially the same rate both in the sea water and when partially embedded in the bottom sediments. Their corrosion rates at the 2,500 foot depth were also essentially constant. The corrosion rates in the sea water at the 2,500 foot depth were essentially the same as those at the 6,000 foot depth while those in the bottom sediments were slightly lower. The corrosion rate of G bronze at a depth of 4,250 feet in the Atlantic Ocean, Reference 13, was essentially the same as at the 6,000 foot depth after 200 days of exposure. Both alloys (G and modified G bronze) corroded at higher rates than at either depth when completely submerged at the surface in the Pacific Ocean at Point Mugu, California. After 181 days of exposure, their corrosion rates were the same (1.3 MPY) and were higher than the average corrosion rate at the 6,000 foot depth by 0.9 MPY. Both alloys corroded uniformly except for some crevice corrosion of modified G bronze after 751 days of exposure in the sediment and 1064 days of exposure in the sea water at the 6,000 foot depth.

Two other bronzes, "M" and leaded tin bronze, similar in chemical composition to modified G bronze, except for the addition of lead, corroded similarly to the G bronzes as shown in Figure 23. A comparison of the curves in Figures 22 and 23 shows that they are practically identical. "M" bronze corroded at essentially the same rate at a depth of 4,250 feet in the Atlantic Ocean, Reference 13, as at a depth of 6,000 feet in the Pacific Ocean. At the surface in the Pacific Ocean the "M" bronze and leaded tin bronze corroded at higher rates than at either depth as shown in Figure 23. The "M" and leaded tin bronzes corroded uniformly except for severe general corrosion of the leaded tin bronze specimen after 751 days of exposure at a depth of 6,000 feet.

The corrosion rates of the phosphor bronzes, "A" and "D", are shown in Figure 24. They corroded uniformly and at the same rate at both depths, 2,500 and 6,000 feet, both in sea water and in the bottom sediments. The corrosion rate decreased between 123 and 400 days of exposure and remained constant thereafter. Phosphor bronze "A", exposed at a depth of 5,600 feet in the Atlantic Ocean, Reference 12, corroded at the same rate as at the 6,000 foot depth in the Pacific Ocean. Both bronzes corroded at higher rates at the surface in the Pacific Ocean at Point Mugu, California than at either depth. Phosphor bronze "A" corroded at higher rates at the surface in the Pacific Ocean, in the Panama Canal Zone, Reference 16, and in Port Hueneme Harbor, California, Reference 15, than at either depth in the Pacific Ocean. The corrosion rates at both locations decreased asymptotically with increasing time of exposure. Also, the corrosion rate of phosphor bronze "A" in the surface sea water at Point Mugu after six months of exposure was higher than in Port Hueneme Harbor.

Wrought aluminum bronzes containing 5 and 7 percent aluminum corroded at essentially the same rate irrespective of depth (2,500 and 6,000 feet) and whether or not they were in sea water or partially embedded in the bottom sediments, Figure 25. The 5 percent aluminum bronze also corroded at the same rate at both depths as it did at the surface in the Pacific Ocean at the Panama Canal Zone, Reference 16, and in Port Hueneme Harbor, Reference 15. After 181 days of exposure at the surface in the Pacific Ocean at Point Mugu, the corrosion rate of 5 percent aluminum bronze was 1.1 MPY, slightly higher than at any of the other locations, both surface and at depth. The 7 percent aluminum bronze corroded the same at the surface at Point Mugu as at the other locations except for one lot of specimens which were dealuminified and corroded at nearly 3 MPY. Their corrosion rates in the sea water and in the bottom sediments at both depths decreased slightly with increasing time of exposure.

The corrosion rates of the cast aluminum bronzes containing 10, 11, and 13 percent aluminum are shown in Figure 26. The corrosion rates in the bottom sediments at the 6,000 foot depth were the same as in the sea water irrespective of the aluminum content. They were the same for the first 751 days of exposure and decreased slightly after 1064 days of exposure at the 6,000 foot depth. At the 2,500 foot depth the corrosion rates in sea water were slightly lower than at the 6,000 foot depth and in the bottom sediments at 2,500 feet, the corrosion rates were lower still, less than 0.1 MPY after 402 days of exposure. After 181 days of exposure at the surface at Point Mugu, the corrosion rates of the 10 and 13 percent aluminum bronzes were considerably higher than at either depth, 2.1 MPY versus 0.5 MPY at 6,000 feet. All three of the alloys were attacked by dealuminification varying in degree from very slight to severe; the first evidence being found after 123 days of exposure at the 6,000 foot depth and 181 days of exposure at the surface.

Although the corrosion rates of the wrought and cast aluminum bronzes were approximately the same as evidenced by comparing Figures 25 and 26 the types of corrosion were different: all the cast alloys were dealuminified while there was dealuminification and pitting on about half of the wrought 7 percent aluminum bronze specimens and uniform corrosion on most of the wrought 5 percent aluminum bronze specimens.

Williams, Reference 17, has reported that dealuminification was found on wrought aluminum bronze containing 6.5 - 11 percent aluminum after exposure in sea water and that an aluminum bronze containing 6 to 8 percent aluminum and 3.5 percent iron was not attacked by dealuminification. In this investigation slight dealuminification was found on an aluminum bronze containing 4.76 percent aluminum and less than 0.05 percent iron at the 6,000 foot depth. There was more dealuminification on two lots of aluminum bronze containing about 7 percent aluminum and 3 percent iron at both the 2,500 and 6,000 foot depths. The performance of the aluminum bronzes at depth in the Pacific Ocean was contrary to that found at the surface in the Atlantic Ocean.

The corrosion rates of the three nickel-aluminum bronze alloys are shown in Figure 27. The corrosion rates in sea water and the bottom sediments were the same irrespective of the depth, 2,500 and 6,000 feet. This shows that variations in the nickel content from 4 to 5 percent, in the aluminum content from 9 to 11 percent, or in the manganese content from 0.5 to 3 percent had no effect on the corrosion of these alloys. Nickel-aluminum bronze No. 2 tended to corrode at a slightly higher rate at a depth of 4,250 feet in the Atlantic Ocean, Reference 13, than at either depth in the Pacific Ocean. Also, nickel-aluminum alloy No. 2 exposed at the surface in the Pacific Ocean at Point Mugu corroded at a rate nearly three times greater than at either depth in the Pacific Ocean. The corrosion rates at depth decreased slightly during the first year of exposure and thereafter, became constant with increasing time of exposure. In addition to the uniform type of corrosion there was some pitting and crevice corrosion and slight dealuminification.

The corrosion rates of the silicon bronzes (3 percent silicon and 3 percent silicon - 1 percent manganese (silicon bronze A)) are shown in Figure 28. Both silicon bronzes corroded at the same rate in sea water and in the bottom sediments at the 6,000 foot depth and the corrosion rate decreased gradually with increasing time of exposure. At the 2,500 foot depth their corrosion rates in sea water and in the bottom sediments were lower than at the 6,000 foot depth with those in the bottom sediment being lower than those in the sea water. In general, the corrosion rates at a depth of 2,500 feet were constant with time. The corrosion rate of 3 percent silicon bronze at the surface of the Pacific Ocean, Panama Canal Zone, Reference 16, decreased sharply between one and two years of exposure and thereafter, became constant with increasing time of exposure; and, after two years of exposure was the same as at the 6,000 foot depth in the Pacific Ocean. After 181 days of exposure at the surface of the Pacific Ocean at Point Mugu, the corrosion rates of the silicon bronzes were about the same as at the 6,000 foot depth. In general, the silicon bronzes were uniformly corroded except for some selective attack at the 6,000 foot depth. This attack is designated "coppering" because of the thin layer of copper on the surfaces of the specimens after exposure. It is postulated that the silicon is either selectively removed by corrosion or that the alloy corrodes as such and copper is subsequently redeposited on the surface of the specimens.

The corrosion rates of the Ni-Vee bronzes A, B and C (copper - nickel - tin - zinc alloys) are shown in Figure 29. They corroded at essentially the same rates in sea water and in the bottom sediments at the 6,000 foot depth and in sea water at the 2,500 foot depth. They decreased slightly and became asymptotic with increasing time of exposure. The corrosion rates were less than 0.1 MPY (insignificant) in the bottom sediments at the 2,500 foot depth. After periods of exposure of 2 years or more at the 6,000 foot depth, the corrosion rates were less than 0.5 MPY except for Ni-Vee bronze A and C in sea water after 751 days of exposure and Ni-Vee bronze A after 1064 days of exposure. There was one area of very severe corrosion on Ni-Vee bronze A after 751 days of exposure and a pit 20 mils deep after 1064 days of exposure in the sea water. There was general corrosion of Ni-Vee bronze C after 751 days of exposure in the sea water. Except for the three cases mentioned above, the corrosion on these three alloys was of the uniform type. After 181 days of exposure at the surface in the Pacific Ocean at Point Mugu, these three alloys corroded at much higher rates than at either depth, 1.9 MPY versus 0.7 MPY.

The corrosion rates of all the bronzes both in sea water and in the bottom sediments at both nominal depths of 2,500 and 6,000 feet are summarized in Figure 30. Initially, all the corrosion rates except those for the silicon bronzes were within the range of less than 0.1 to 0.8 MPY while those for the silicon bronzes at the 6,000 foot depths were about twice as high (1.3 to 1.7 MPY). However, after 1064 days of exposure at the 6,000 foot depth, the corrosion rates of all the alloys were within the range of less than 0.1 MPY to 0.7 MPY. At the 2,500 foot depth the ranges were between less than 0.1 to 0.8 MPY after 197 days and less than 0.1 to 0.6 MPY after 402 days of exposure. In general, it can be concluded that the bronzes corroded at nearly constant rates except for the silicon bronzes which corroded at decreasing rates with increasing time of exposure. There were a few values which were outside these ranges, most of them (6 of 8) after 751 days of exposure at a depth of 6,000 feet: they were aluminum bronzes, nickel-aluminum bronzes and silicon bronzes. Most of the bronzes corroded at greater rates at the surface in the Pacific Ocean at Point Mugu than at either depth; the only exception was the silicon bronzes which corroded at the same rate as at the 6,000 foot depth.

Stress Corrosion

Four of the bronze alloys, phosphor bronze A, phosphor bronze D, aluminum bronze and manganese-silicon bronze were exposed in the stressed condition to determine their susceptibility to stress corrosion cracking. They were stressed at values equivalent to 35, 50 and 75 percent of their respective yield strength as shown in Table 12. They were not susceptible to stress corrosion cracking for periods of exposure of 400 days at either depth.

Mechanical Properties

The effects of exposure in the deep ocean environments on the mechanical properties of the bronzes are given in Table 13 and shown in Figures 31 through 34. The mechanical properties of the phosphor bronzes, A and D, (Figures 31 and 32) were not affected by exposures for as long as 402 days at a depth of 2,500 feet or 751 days at a depth of 6,000 feet. The elongation of the aluminum bronze (Figure 33) was decreased considerably (28%) especially after 403 and 751 days at the 6,000 foot depth which is attributed to pitting corrosion and dealuminification. The tensile strength, yield strength and elongation of silicon bronze A (Figure 34) were seriously decreased after 403 days of exposure in the bottom sediment at a depth of 6,000 feet. This decrease in mechanical properties is attributed to the severe selective corrosion (coppering) of the alloy.

Corrosion Products

Chemical determinations of the corrosion products removed from aluminum bronze showed the presence of copper oxy-chloride, cupric chloride; major elements, copper and aluminum; minor elements, iron, magnesium, calcium and silicon; chloride ion, 0.9%, and sulfate ion, 9.0%.

COPPER-NICKEL ALLOYS

The chemical compositions of the copper-nickel (Cu-Ni) alloys are given in Table 14, their corrosion rates and types of corrosion in Table 15, stress corrosion tests in Table 16 and changes in mechanical properties due to corrosion in Table 17.

Corrosion

The corrosion rates and types of corrosion of the copper-nickel alloys are given in Table 15 and are shown graphically in Figures 35 to 45.

There were three different lots of 90 copper-10 nickel alloy exposed at depths in the Pacific Ocean. As shown in Figure 35, their corrosion rates in sea water at the 6,000 foot depth were comparable. The corrosion rates of the specimens partially embedded in the bottom sediments at the 6,000 foot depth were slightly lower than those in the sea water. At the 2,500 foot depth the corrosion rates in sea water were comparable with those in sea water at the 6,000 foot depth. In the bottom sediment at the 2,500 foot depth the corrosion rates were lower than those in the sea water. The corrosion rates after 181 days of exposure at the surface in the Pacific Ocean at Point Mugu were practically the same as those at both depths. At a depth of 5,600 feet in the Atlantic Ocean, 90 copper-10 nickel alloy, after 110 days of exposure, corroded at the same rate as at 6,000 feet in the Pacific Ocean but, after 1050 days of exposure, its corrosion rate was much less than in the Pacific Ocean, Reference 12. The same was true after 100 days of exposure at a depth of 4,250 feet in the Atlantic Ocean, Reference 13, and after 200 days of exposure the corrosion rate was slightly lower than in the Pacific Ocean. The corrosion was uniform with the specimens being covered with thin light green flaky films of corrosion products.

The corrosion rates of the 70 copper-30 nickel with nominal 0.5 percent iron are shown in Figure 36. The corrosion behavior of this alloy was very similar to that of the 90 copper-10 nickel alloy at the 6,000 foot depth. The corrosion rate in the bottom sediment after 123 days at the 6,000 foot depth was lower than that in the sea water but after 1064 days, the rates were the same. The corrosion rates at the 2,500 foot depth were lower than those at the 6,000 foot depth and those in the bottom sediments were lower than those in the sea water. The corrosion rates at depths of 4,250 and 4,500 feet in the Atlantic Ocean, Reference 13, were lower than those in sea water at the 6,000 foot depth in the Pacific Ocean and decreased with increasing time of exposure. The corrosion rate at the surface in the Pacific Ocean at Point Mugu were lower than those in sea water at both depths. At the surface in the Pacific Ocean at the Panama Canal Zone, the corrosion rates also were less than in the sea water at both depths, Reference 16. The corrosion of this alloy was uniform with the surfaces of the specimens being covered with light green, flaky corrosion products.

The corrosion rates of 70 copper-30 nickel alloy containing 5 percent iron were very low as shown in Figure 37. They were the same in the bottom sediments as in the sea water at both depths, 2,500 and 6,000 feet. The corrosion rates at the 6,000 foot depth increased between 403 and 751 days of exposure. This increase is attributed to the change in the protective film on this alloy. Through 400 days of exposure at both depths the specimens were protected by a thin, hard, black shiny film which deteriorated during longer exposure time causing crevice corrosion and pitting with some selective attack (coppering). There were copious deposits of copper on the specimens, especially in pits and at faying surfaces. The corrosion rate at the surface after 181 days of exposure in the Pacific Ocean at Point Mugu was considerably higher than at either depth and the alloy was attacked by crevice corrosion to a depth of 5 mils. At a depth of 4,250 feet in the Atlantic Ocean, Reference 13, this alloy corroded at a higher rate than at either depth in the Pacific Ocean but at the same rate as at the surface in the Pacific Ocean.

The corrosion rates of the three copper-nickel alloys (90-10, 70-30 with 0.5% Fe, and 70-30 with 5% Fe) are plotted in Figure 38 to show that at the 6,000 foot depth the corrosion rates of the 90 copper-10 nickel and 70 copper-30 nickel with 0.5% Fe are comparable both in the sea water and bottom sediments with the rates in the bottom sediments being just below those in the sea water. At the 2,500 foot depth, the corrosion rates in the sea water were comparable with those in the bottom sediments at the 6,000 foot depth while those in the bottom sediments at the 2,500 foot depth were lower than those in the sea water. The corrosion rates of the 70 copper-30 nickel with 5% Fe were lower than those of the other two alloys at both depths in sea water and in the bottom sediments except in the sea water at the 6,000 foot depth after 751 days of exposure. In this case, the corrosion rate was about the same as the other two alloys.

The corrosion of 95 copper-5 nickel was uniform, the corrosion rates were the same in the sea water and in the bottom sediments, and decreased asymptotically with increasing time of exposure at the 6,000 foot depth as shown in Figure 39. At the 2,500 foot depth, the corrosion rate in sea water was uniform with increasing time of exposure and was the same as at the 6,000 foot depth after 400 days of exposure. In the bottom sediments at the 2,500 foot depth, the corrosion rate increased slightly with time of exposure and after 400 days was the same as at the 6,000 foot depth.

The corrosion rates of 80 copper-20 nickel alloys are shown in Figure 40. The alloys differed in chemical composition with regard to their iron contents; the one exposed by NCEL contained 0.62 percent iron while the one exposed for the International Nickel Company, Inc. contained 0.03 percent iron. The differences in their corrosion rates are attributed to the difference in their iron contents. This is clearly shown in Figure 40 where, in sea water at both depths, the corrosion rates of the alloy with 0.03 percent iron were higher than those of the alloy which contained 0.62 percent iron. The reverse was found in the specimens exposed in the bottom sediments. The corrosion rate of the alloy with 0.03 percent iron after 181 days of exposure at the surface in the Pacific Ocean was higher than those for the same alloy at both depths. The corrosion was, in general, uniform.

The corrosion rates of 55 copper-45 nickel alloy (a thermocouple alloy) are shown in Figure 41. The alloy corroded uniformly except for crevice corrosion to perforation after 1064 days of exposure in the bottom sediment at the 6,000 foot depth. The corrosion rates initially increased with time, then became constant at about 1.0 MPY at the 6,000 foot depth in sea water while in the bottom sediments, they initially decreased with increasing time of exposure, then became constant at about 0.5 MPY. At the 2,500 foot depth the corrosion rates both in sea water and in the bottom sediments decreased with increase in duration of exposure. At both depths the corrosion rates in the bottom sediments were lower than those in the sea water. After 181 days of exposure at the surface in the Pacific Ocean, the corrosion rate of the alloy was much higher than at either depth.

The corrosion rates of a nickel-silver (65 Cu - 18 Ni - 17 Zn) are shown in Figure 42. At the 6,000 foot depth, the corrosion rates both in sea water and in the bottom sediments decreased rapidly with increasing time of exposure. The corrosion rates at the 2,500 foot depth were essentially constant with time and those in the bottom sediments were very low and much lower than those in the sea water. After 181 days of exposure at the surface and 197 days of exposure in the sea water at a depth of 2,500 feet in the Pacific Ocean, the corrosion rates were practically the same. The corrosion rate of this alloy at the surface in the Pacific Ocean at the Panama Canal Zone was very low (0.03 MPY) and constant with time of exposure. The type of corrosion was uniform.

The corrosion rates of a copper-nickel-zinc-lead alloy are shown in Figure 43. The corrosion rates in sea water and in the bottom sediments at the 6,000 foot depth were comparable and decreased gradually with increasing time of exposure. The corrosion rates at the 2,500 foot depth were lower than those at the 6,000 foot depth and those in the bottom sediments were lower than those in sea water. The corrosion rate after 181 days of exposure at the surface in the Pacific Ocean at Point Mugu was about the same as in the sea water at the 6,000 foot depth. The corrosion of this alloy was of the uniform type.

The corrosion rates in sea water at the 2,500 and 6,000 foot depths of all the copper-nickel alloys given in Table 14 and shown in Figures 35 through 43 are shown within bands in Figure 44. At the 6,000 foot depth, the band narrows and decreases asymptotically with increasing time of exposure to a width of 0.5 MPY after 1064 days. The arithmetical average curve is located about the midpoint of the width of the band. The band for the 2,500 foot depth is practically constant with time and the average curve practically bisects it. From these bands it can be concluded that the corrosion rates of the copper-nickel alloys in sea water can be expected to decrease with increasing duration of exposure and to corrode at between 0.5 and 1 MPY at depth in the Pacific Ocean after about 3 years at a depth of 6,000 feet and after about 1 year at a depth of 2,500 feet. The only alloy whose corrosion rates did not come within these bands was the 70 copper-30 nickel alloy which contained 5 percent iron. However, at the 6,000 foot depth its corrosion rate increased when the protective film failed locally and after 751 days it was nearly as great as those of the other alloys.

Similar bands encompassing the corrosion rates of the copper-nickel alloys when partially embedded in the bottom sediments are shown in Figure 45. The lines within the bands are the average curves. At the 6,000 foot depth the band narrows and decreases asymptotically with increasing time of exposure to a width of about 0.3 MPY after 1064 days of exposure. From this band it can be concluded that the corrosion rates of the copper-nickel alloys partially embedded in the bottom sediments can be expected to decrease with increasing duration of exposure and to corrode at between 0.2 and 0.5 MPY after about 3 years of exposure. At the 2,500 foot depth there was a slight increase in the width of the band between 200 and 400 days of exposure and the average corrosion rate curve also increased slightly. After 1064 days of exposure at a depth of 6,000 feet, the copper-nickel alloys partially embedded in the bottom sediments corroded at slower rates than in the sea water as shown by comparing Figures 44 and 45.

Stress Corrosion

Five of the copper-nickel alloys were exposed in the stressed condition to determine their susceptibility to stress corrosion cracking, Table 16. They were stressed at values equivalent to 35, 50 and 75 percent of their respective yield strengths. None of the alloys were susceptible to stress corrosion cracking at depths of 2,500 and 6,000 feet for periods of exposure of 400 days.

Mechanical Properties

The effects of exposure in the deep ocean environments on the mechanical properties of the copper-nickel alloys are given in Table 17. The mechanical properties of none of the alloys were adversely affected by exposures of 400 days at the 2,500 foot depth or of 750 days at the 6,000 foot depth.

Corrosion Products

Qualitative chemical analyses of the corrosion products removed from 70 percent copper-30 percent nickel-5 percent iron exposed for 751 days at a depth of 6,000 feet showed that they were composed of nickel hydroxide ($Ni(OH)_2$); cupric chloride ($Cu\ Cl_2$); major elements, copper and nickel; minor elements, iron, magnesium, sodium, and traces of silicon and manganese; chloride ion as Cl, 4.77%; sulfate ions as SO_4, 0.80%; copper as metal, 43.63%.

SUMMARY AND CONCLUSIONS

The purpose of this investigation was to determine the effects of deep ocean environments on the corrosion of copper and copper alloys. To accomplish this a total of 1050 specimens of 46 different alloys were exposed at nominal depths of 2,500 and 6,000 feet for periods of time varying from 123 to 1064 days.

Copper

Copper and beryllium-copper corroded uniformly at all depths but copper was pitted during surface exposure in the Pacific Ocean at Point Mugu. The corrosion rates were practically constant and of the same magnitude after exposure for one year in sea water at the surface and at all depths in the Atlantic and Pacific Oceans. In the bottom sediments at the 6,000 foot depth the corrosion rates decreased with increasing time of exposure and were the same as those in the sea water after 35 months of exposure. At the 2,500 foot depth the corrosion rates both in sea water and in the bottom sediments were lower than at the 6,000 foot depth. Copper corroded at the same rate at the surface in the Pacific Ocean at Point Mugu as at depth.

The addition of 2 percent beryllium to copper did not affect its corrosion rate. Neither MIG nor TIG welding affected the corrosion rate of beryllium-copper.

Copper was not susceptible to stress corrosion cracking at a depth of 2,500 feet in the Pacific Ocean.

The mechanical properties of copper and beryllium-copper were not adversely affected by exposure at depth in the Pacific Ocean for periods of time of up to 2 years.

Copper-Zinc Alloys (Brasses)

Except for Muntz metal and manganese bronze the copper-zinc alloys corroded at rates which decreased asymptotically with increasing duration of exposure both in sea water and in the bottom sediments at the 6,000 foot depth. After 35 months of exposure the corrosion rates were between 0.2 and 0.8 MPY. At the 2,500 foot depth the corrosion rates in sea water were about the same as at the 6,000 foot depth but in the bottom sediments at 2,500 feet the rates were lower than in the sea water at 2,500 feet and in the bottom sediments at 6,000 feet. The non-conformity of Muntz metal and manganese bronze with the behavior of the other copper-zinc alloys is attributed to the dezincification of these two alloys.

Commercial bronze, red brass, commercial brass, yellow brass, Muntz metal, Naval brass, Tobin bronze, manganese bronze and nickel-manganese bronze were dezincified while arsenical admiralty brass, aluminum brass and nickel brass were not dezincified.

Most of the copper-zinc alloys corroded at faster rates at the surface in the Pacific Ocean at Point Mugu than at depth. Commercial bronze and Naval brass corroded at slower rates, Muntz metal at a faster rate, and manganese bronze at the same rate at depth as at the surface in the Pacific Ocean at the Panama Canal Zone.

Arsenical admiralty brass and Muntz metal were not susceptible to stress corrosion cracking at depth in the Pacific Ocean.

The mechanical properties of arsenical admiralty brass were not adversely affected by exposure at depth in the Pacific Ocean while those of Muntz metal and nickel-manganese bronze were adversely affected.

Corrosion products consisted of cupric chloride ($Cu\ Cl_2$), copper hydroxy-chloride ($Cu_2(OH)_3Cl$) and metallic copper, 36 percent.

Bronzes

Except for the silicon bronzes, the bronzes corroded essentially at constant rates with increasing duration of exposure both in sea water and in the bottom sediments at depths of 2,500 and 6,000 feet in the Pacific Ocean. The corrosion rates of the silicon bronzes initially were higher than the other bronzes but after 35 months of exposure at the 6,000 foot depth they were comparable with the other bronzes. The corrosion rates of the bronzes were higher at the surface in the Pacific Ocean at Point Mugu than at depth.

The corrosion rate of phosphor bronze A was higher at the surface in the Pacific Ocean at the Panama Canal Zone and in Port Hueneme Harbor than at depth while those for silicon bronze and 5 percent and

7 percent aluminum bronzes were about the same at the Panama Canal Zone as at depth.

The bronzes, except the aluminum bronzes, nickel-aluminum bronze containing 10 percent aluminum and the silicon bronzes, were corroded uniformly. These bronzes were attacked by selective corrosion whereby either aluminum or silicon was selectively removed with a layer of metallic copper remaining on the surfaces of the specimens. Where an alloy is corroded by this type of attack, corrosion rates are not a true indication of the amount of corrosion because the weight losses are low due to the weight of redeposited copper remaining on the specimens. Hence in these cases, corrosion rates are not reliable indications of corrosion damage.

Phosphorous bronzes A and D, 7 percent aluminum bronze and silicon bronze A were not susceptible to stress corrosion cracking at depths of 2,500 and 6,000 feet in the Pacific Ocean.

The mechanical properties of the phosphorous bronzes A and D were not adversely affected by exposure at depth in the Pacific Ocean while those of 7 percent aluminum bronze and silicon bronze A were adversely affected. This adverse effect is attributed to the selective corrosion of the 7 percent aluminum bronze and the silicon bronze A.

Corrosion products were copper oxy-chloride ($CuCl_2 \cdot 3CuO \cdot 4H_2O$) and cupric chloride ($CuCl_2$).

Copper-Nickel Alloys

The corrosion rates of the copper-nickel alloys in sea water and in the bottom sediments at both the 2,500 and 6,000 foot depths decreased with increasing duration of exposure. However, the corrosion rates in the bottom sediments were lower than those in sea water. Copper-nickel alloy, 70 percent copper-30 percent nickel containing 5 percent iron corroded at much lower rates in sea water at both depths through 400 days of exposure than did the other alloys. These lower corrosion rates are attributed to the protection afforded the alloy by the hard, impervious film on its surface which did not start to deteriorate until after 400 days of exposure; thereafter, the corrosion rates increased. The copper-nickel alloys, 70-30 containing 5 percent iron, 80-20 and 55-45 corroded at faster rates at the surface in the Pacific Ocean at Point Mugu than at either depth; those of 90-10 and Cu-Ni-Zn-Pb alloys were the same at the surface and at depth; and those of 70-30 containing 0.5 percent iron and nickel-silver were lower at the surface than at depth. The 70-30 alloy with 0.5 percent iron corroded at the same rate after 2 years of exposure at depth as it did at the surface of the Pacific Ocean at the Panama Canal Zone.

Copper-nickel alloys 95-5, 90-10, 80-20, 70-30 containing 0.5 percent iron, nickel-silver and Cu-Ni-Zn-Pb corroded uniformly. The 70-30 alloy containing 5 percent iron was attacked by crevice and pitting corrosion after 751 days of exposure at the 6,000 foot depth and the

55-45 alloy was perforated by crevice corrosion after 1064 days of exposure at the 6,000 foot depth.

Copper-nickel alloys 95-5, 90-10, 80-20, 70-30 containing 0.5 percent and 5 percent iron were not susceptible to stress corrosion cracking at either depth in the Pacific Ocean.

The mechanical properties of 95-5, 90-10, 80-20, 70-30 containing 0.5 percent iron and 70-30 containing 5 percent iron copper-nickel alloys were not adversely affected by exposure at either depth in the Pacific Ocean.

Corrosion products on 70-30 copper-nickel alloy containing 5 percent iron were nickel hydroxide ($Ni(OH)_2$), cupric chloride ($CuCl_2$) and copper metal, 44 percent.

Because of the selective corrosion of the majority of the copper-zinc alloys, the aluminum bronzes, nickel-aluminum bronze containing 10 percent aluminum and the silicon brzones, they would be unsatisfactory for use in sea water applications, especially for long periods of constant immersion at depth.

Copper, beryllium-copper, arsenical admiralty brass, aluminum brass, nickel brass, the bronzes except the aluminum bronzes, nickel-aluminum bronze containing 10 percent aluminum and the silicon bronzes, and the nickel-copper alloys would be satisfactory for deep submergence applications because of their low corrosion rates, uniform type of corrosion, non-susceptibility to stress corrosion cracking, and no adverse effect on their mechanical properties.

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Table 1. STU Locations and Bottom Water Characteristics

Site No.	Lat. N	Longit. W	Depth, ft	Exposure, Days	Temp. $^{\circ}C$	Oxygen, ml/l	Salinity, ppt	pH	Current Knots, Av.
Surface	-	-	65	-	11-17	5.4-6.5	33.76	7.9-8.3	Variable
I-1	$33^{\circ}46'$	$120^{\circ}37'$	5300	1064	2.6	1.2	34.51	7.5	0.03
I-2	$33^{\circ}44'$	$120^{\circ}45'$	5640	751	2.3	1.3	34.51	7.6	0.03
I-3	$33^{\circ}44'$	$120^{\circ}45'$	5640	123	2.3	1.3	34.51	7.6	0.03
I-4	$33^{\circ}46'$	$120^{\circ}46'$	6780	403	2.2	1.6	34.40	7.7	0.03
II-1	$34^{\circ}06'$	$120^{\circ}42'$	2340	197	5.0	0.4	34.36	7.5	0.06
II-2	$34^{\circ}06'$	$120^{\circ}42'$	2370	402	5.0	0.4	34.36	7.5	0.06
V	$34^{\circ}06'$	$119^{\circ}07'$	5	181	12-19	3.9-6.6	33.51	8.1	Variable

Table 2. Chemical Composition of Coppers, Percent by Weight

Alloy	CDA No.[1]	Cu	Ni	Be	Co	Source[2]
Copper, O Free	102	99.96	-	-	-	NCEL
Copper, O Free	102	99.9	-	-	-	INCO[9]
Copper, O Free	102	99.97	-	-	-	NCEL[11]
Be-Cu	172	97.80	0.05	1.90	0.25	NCEL
Be-Cu Chain[3]	172	Rem.[4]	-	2.0	0.5	NCEL

[1] Copper Development Association alloy number

[2] Numbers refer to references at end of paper

[3] Cast alloy

[4] Remainder

Table 3. Corrosion Rates and Types of Corrosion of Coppers

Alloy	CDA No.[1]	Environ-ment[2]	Exposure, Days	Depth, Feet	Corrosion Rate, MPY	Type of Corrosion[4]	Source[3]
Copper, O Free	102	W	123	5640	1.6	U	NCEL
Copper, O Free	102	W	123	5640	1.5	U	INCO[9]
Copper, O Free	102	S	123	5640	1.3	U	NCEL
Copper, O Free	102	S	123	5640	1.5	U	INCO[9]
Copper, O Free	102	W	403	6780	1.2	U	NCEL
Copper, O Free	102	W	403	6780	1.3	U	INCO[9]
Copper, O Free	102	S	403	6780	1.1	U	NCEL
Copper, O Free	102	S	403	6780	<0.1	U	INCO[9]
Copper, O Free	102	W	751	5640	0.7	U	NCEL
Copper, O Free	102	W	751	5640	1.0	U	INCO[9]
Copper, O Free	102	S	751	5640	0.7	U	INCO[9]
Copper, O Free	102	W	1064	5300	0.5	U	NCEL[11]
Copper, O Free	102	W	1064	5300	0.5	U	INCO[9]
Copper, O Free	102	S	1064	5300	0.3	G	INCO[9]
Copper, O Free	102	W	197	2340	0.8	U	NCEL
Copper, O Free	102	W	197	2340	1.4	U	INCO[9]
Copper, O Free	102	S	197	2340	0.2	U	NCEL
Copper, O Free	102	S	197	2340	0.2	U	INCO[9]
Copper, O Free	102	W	402	2370	0.9	U	NCEL
Copper, O Free	102	W	402	2370	1.4	U	INCO[9]
Copper, O Free	102	S	402	2370	0.6	U	NCEL
Copper, O Free	102	S	402	2370	0.2	ET	INCO[9]
Copper, O Free	102	W	181	5	1.4	P, 22m	NCEL
Be-Copper	172	W	402	2370	0.6	U	NCEL
Be-Copper	172	S	402	2370	0.5	U	NCEL
Be-Copper	172	W	181	5	0.1	U	NCEL

Table 3. Corrosion Rates and Types of Corrosion of Coppers (cont'd)

Alloy	CDA No.[1]	Environment[2]	Exposure, Days	Depth, Feet	Corrosion Rate, MPY	Type of[4] Corrosion	Source[3]
Be-Copper[5]	172	W	402	2370	0.5	U[7]	NCEL
Be-Copper[5]	172	S	402	2370	0.5	U[7]	NCEL
Be-Copper[5]	172	W	181	5	0.1	U[7]	NCEL
Be-Copper[6]	172	W	402	2370	0.6	ET	NCEL
Be-Copper[6]	172	S	402	2370	0.5	ET	NCEL
Be-Copper[6]	172	W	181	5	0.1	ET	NCEL
Be-Copper, chain[8]	172	W	402	2370	0.5	U	NCEL
Be-Copper, chain[8]	172	S	402	2370	0.4	U	NCEL
Be-Copper, chain[8]	172	W	181	5	0.1	U	NCEL

1/ Copper Development Association alloy numbers.

2/ W - Totally exposed in sea water on sides of structure.
S - Exposed in base of structure so that the lower portions of the specimens were embedded in the bottom sediments.

3/ Numbers refer to references at end of paper.

4/ Symbols for types of corrosion

C - Crevice
ET - Etching

Table 3. Corrosion Rates and Types of Corrosion of Coppers (cont'd)

4/ Symbols for types of corrosion (cont'd)

G - General
U - Uniform
Numbers indicate mils
i.e. 20 - 20 mils
20m - 20 mils maximum
14.6a - 14.6 mils average

5/ MIG weld

6/ TIG weld

7/ Uniform, weld bead etched

8/ Cast

Table 4. Stress Corrosion of Copper

Alloy	CDA No.[1]	Stress, KSI	Yield Strength, o/o	Exposure		Specimens	
				Days	Depth, Feet	Exposed	Failed
Copper, O Free	102	10.6	75	197	2340	3	0
Copper, O Free	102	10.6	75	402	2370	3	0

[1] Copper Development Association alloy number

Table 5. Changes in Mechanical Properties of Coppers Due to Corrosion

Alloy	CDA No.[1]	Exposure		Original Properties			Percent Change		
		Days	Depth, Feet	Tensile Strength, KSI	Yield Strength, KSI	Elongation, Percent	Tensile Strength	Yield Strength	Elongation
Copper, O Free	102	-	-	33.4	14.2	52.0	-	-	-
Copper, O Free	102	123	5640	-	-	-	+1.5	-5.6	-1.9
Copper, O Free	102	403	6780	-	-	-	+0.3	+8.5	-5.6
Copper, O Free	102	751	5640	-	-	-	+3.6	+11.1	-5.8
Copper, O Free	102	197	2340	-	-	-	-7.8	-18.3	-3.7
Copper, O Free	102	402	2370	-	-	-	+2.3	+3.5	-6.5
Be-Cu	172	-	-	176.2	162.1	3.5	-	-	-
Be-Cu	172	402	2370	-	-	-	-9.0	-7.6	-14.3
Be-Cu[2]	172	-	-	160.8	157.5	3.3	-	-	-
Be-Cu[2]	172	402	2370	-	-	-	-4.7	-2.0	+18.2
Be-Cu[3]	172	-	-	166.4	162.2	3.0	-	-	-
Be-Cu[3]	172	402	2370	-	-	-	-0.8	-5.6	-16.7

[1] Copper Development Association alloy number

[2] MIG weld

[3] TIG weld

Table 6. Chemical Composition of Copper-Zinc Alloys (Brasses), Percent by Weight

Alloy	CDA No.[1]	Cu	Zn	Sn	Ni	Al	Mn	Fe	Other	Source[2]
Commercial Bronze	220	90	10	-	-	-	-	-	-	INCO[9]
Red Brass	230	85	15	-	-	-	-	-	-	INCO[9]
Commercial Brass	268	66.47	33.51	<0.05	-	-	-	0.02	<0.01 Pb	NCEL[11]
Yellow Brass	268	68.48	31.50	<0.05	-	-	-	0.02	<0.01 Pb	NCEL[11]
Arsenical Admiralty	443	71.19	27.77	1.00	-	-	-	0.01	0.027As	NCEL
Arsenical Admiralty	443	70.0	29.0	1.0	-	-	-	-	0.04As	INCO[9]
Yellow Brass	270	65.0	35.0	-	-	-	-	-	-	INCO[9]
Muntz Metal	280	60.69	39.29	-	-	-	-	<0.02	-	NCEL
Muntz Metal	280	60.0	40.0	-	-	-	-	-	-	INCO[9]
Naval Brass	464	60.46	38.74	0.69	-	-	-	0.03	0.08Pb	NCEL[11]
Tobin Bronze	-	58.94	39.07	0.89	Nil	<0.10	-	1.10	<0.05Pb	NCEL[11]
Mn Bronze A	675	56.0	42.0	-	-	1.0	0.1	1.0	-	INCO[9]
Ni-Mn Bronze[3]	-	54.58	34.48	0.70	3.77	1.73	3.06	1.66	0.02Pb	NCEL
Al Brass	-	78.0	20.0	-	-	2.0	-	-	-	INCO[9]
Ni Brass	-	50.0	40.0	-	8.0	-	-	2.0	-	INCO[9]

[1] Copper Development Association alloy number

[2] Numbers refer to references at end of paper

[3] Cast alloy

Table 7. Corrosion Rates and Types of Corrosion of Copper-Zinc Alloys (Brasses)

Alloy	CDA No.[1]	Environment[2]	Exposure, Days	Depth, Feet	Corrosion Rate, MPY	Type of[4] Corrosion	Source[3]
Commercial Bronze	220	W	123	5640	0.6	U	INCO[9]
Commercial Bronze	220	S	123	5640	0.3	U	INCO[9]
Commercial Bronze	220	W	403	6780	0.6	U	INCO[9]
Commercial Bronze	220	S	403	6780	<0.1	U	INCO[9]
Commercial Bronze	220	W	751	5640	0.6	C, 9	INCO[9]
Commercial Bronze	220	S	751	5640	0.4	C, 20	INCO[9]
Commercial Bronze	220	W	1064	5300	0.4	C, 20	INCO[9]
Commercial Bronze	220	S	1064	5300	0.6	U	INCO[9]
Commercial Bronze	220	W	197	2340	0.3	U	INCO[9]
Commercial Bronze	220	S	197	2340	0.1	NU ET	INCO[9]
Commercial Bronze	220	W	402	2370	0.2	SL DZ	INCO[9]
Commercial Bronze	220	S	402	2370	<0.1	SL DZ	INCO[9]
Commercial Bronze	220	W	181	5	1.1	U	INCO[9]
Red Brass	230	W	123	5640	1.3	U	INCO[9]
Red Brass	230	S	123	5640	1.7	SL DZ	INCO[9]
Red Brass	230	W	403	6780	1.2	SL DZ	INCO[9]
Red Brass	230	S	403	6780	0.4	GBSL	INCO[9]
Red Brass	230	W	751	5640	0.9	SL DZ	INCO[9]
Red Brass	230	S	751	5640	0.7	U	INCO[9]
Red Brass	230	W	1064	5300	0.6	SL DZ	INCO[9]
Red Brass	230	S	1064	5300	0.3	G	INCO[9]
Red Brass	230	W	197	2340	1.0	U	INCO[9]
Red Brass	230	S	197	2340	0.1	U	INCO[9]
Red Brass	230	W	402	2370	0.7	U	INCO[9]
Red Brass	230	S	402	2370	<0.1	ET	INCO[9]
Red Brass	230	W	181	5	1.8	SL DZ	INCO[9]

Table 7. Corrosion Rates and Types of Corrosion of Copper-Zinc Alloys (Brasses) (cont'd)

Alloy	CDA No.[1]	Environment[2]	Exposure, Days	Depth, Feet	Corrosion Rate, MPY	Type of Corrosion[4]	Source[3]
Commercial Brass	268	W	1064	5300	0.8	S DZ	NCEL[11]
Yellow Brass	268	W	1064	5300	0.6	MO DZ	NCEL[11]
As Admiralty	443	W	123	5640	1.0	U	NCEL[9]
As Admiralty	443	W	123	5640	1.1	U	INCO[9]
As Admiralty	443	S	123	5640	1.0	U	NCEL[9]
As Admiralty	443	S	123	5640	1.0	U	INCO[9]
As Admiralty	443	W	403	6780	0.7	U	NCEL[9]
As Admiralty	443	W	403	6780	0.8	U	INCO[9]
As Admiralty	443	S	403	6780	0.8	U	NCEL[9]
As Admiralty	443	S	403	6780	0.2	GBSL	INCO[9]
As Admiralty	443	W	751	5640	0.6	U	NCEL[9]
As Admiralty	443	W	751	5640	0.7	U	INCO[9]
As Admiralty	443	S	751	5640	0.4	U	NCEL[9]
As Admiralty	443	S	751	5640	0.5	U	INCO[9]
As Admiralty	443	W	1064	5300	0.5	U	INCO[9]
As Admiralty	443	S	1064	5300	0.5	U	INCO[9]
As Admiralty	443	W	197	2340	0.6	U	NCEL[9]
As Admiralty	443	W	197	2340	1.0	U	INCO[9]
As Admiralty	443	S	197	2340	0.2	U	NCEL[9]
As Admiralty	443	S	197	2340	<0.1	U	INCO[9]
As Admiralty	443	W	402	2370	0.6	U	NCEL[9]
As Admiralty	443	W	402	2370	0.6	U	INCO[9]
As Admiralty	443	S	402	2370	0.4	U	NCEL[9]
As Admiralty	443	S	402	2370	0.1	ET	INCO[9]
As Admiralty	443	W	181	5	1.3	U	NCEL[9]
As Admiralty	443	W	181	5	1.8	G	INCO[9]

Table 7. Corrosion Rates and Types of Corrosion of Copper-Zinc Alloys (Brasses) (cont'd)

Alloy	CDA No.[1]	Environ-ment[2]	Exposure, Days	Depth, Feet	Corrosion Rate, MPY	Type of[4] Corrosion	Source[3]
Yellow Brass	270	W	123	5640	1.4	U	INCO[9]
Yellow Brass	270	S	123	5640	1.3	U	INCO[9]
Yellow Brass	270	W	403	6780	1.0	U	INCO[9]
Yellow Brass	270	S	403	6780	0.2	GBSL	INCO[9]
Yellow Brass	270	W	751	5640	2.5	SL DZ	INCO[9]
Yellow Brass	270	S	751	5640	0.6	SL DZ	INCO[9]
Yellow Brass	270	W	1064	5300	0.6	U	INCO[9]
Yellow Brass	270	S	1064	5300	0.5	U	INCO[9]
Yellow Brass	270	W	197	2340	0.9	U	INCO[9]
Yellow Brass	270	S	197	2340	0.2	NU ET	INCO[9]
Yellow Brass	270	W	402	2370	0.9	U	INCO[9]
Yellow Brass	270	S	402	2370	0.1	ET	INCO[9]
Yellow Brass	270	W	181	5	2.1	U	INCO[9]
Muntz Metal	280	W	123	5640	1.6	SL DZ	NCEL
Muntz Metal	280	W	123	5640	2.1	U	INCO[9]
Muntz Metal	280	S	123	5640	1.3	SL DZ	NCEL
Muntz Metal	280	S	123	5640	1.5	U	INCO[9]
Muntz Metal	280	W	403	6780	2.6	SL DZ	NCEL
Muntz Metal	280	W	403	6780	3.3	S DZ	INCO[9]
Muntz Metal	280	S	403	6780	1.8	SL DZ	NCEL
Muntz Metal	280	S	403	6780	0.6	GBSL	INCO[9]
Muntz Metal	280	W	751	5640	3.2	G DZ	NCEL
Muntz Metal	280	W	751	5640	4.0	S DZ	INCO[9]
Muntz Metal	280	S	751	5640	1.7	S DZ	INCO[9]
Muntz Metal	280	W	1064	5300	2.3	S DZ	INCO[9]
Muntz Metal	280	S	1064	5300	0.8	U	INCO[9]
Muntz Metal	280	W	197	2340	0.7	SL DZ; P, 10m, 2.3a	NCEL

Table 7. Corrosion Rates and Types of Corrosion of Copper-Zinc Alloys (Brasses) (cont'd)

Alloy	CDA No.[1]	Environ-ment[2]	Exposure, Days	Depth, Feet	Corrosion Rate, MPY	Type of Corrosion[4]	Source[3]
Muntz Metal	280	W	197	2340	0.7	U	INCO[9]
Muntz Metal	280	S	197	2340	0.5	SL DZ; P, 5m, 3a	NCEL
Muntz Metal	280	S	197	2340	<0.1	SL DZ[5]	INCO[9]
Muntz Metal	280	W	402	2370	0.7	SL DZ	NCEL
Muntz Metal	280	W	402	2370	0.7	SL DZ	INCO[9]
Muntz Metal	280	S	402	2370	0.6	SL DZ	NCEL
Muntz Metal	280	S	402	2370	0.1	ET	INCO[9]
Muntz Metal	280	W	181	5	2.4	DZ	NCEL
Muntz Metal	280	W	181	5	3.4	SL DZ	INCO[9]
Naval Brass	464	W	1064	5300	1.0	S DZ	NCEL[11]
Tobin Bronze	-	W	1064	5300	0.9	S DZ	NCEL[11]
Mn Bronze A	675	W	123	5640	2.9	EX DZ	INCO[9]
Mn Bronze A	675	S	123	5640	2.0	EX DZ	INCO[9]
Mn Bronze A	675	W	403	6780	2.7	S DZ	INCO[9]
Mn Bronze A	675	S	403	6780	0.9	S DZ	INCO[9]
Mn Bronze A	675	W	751	5640	7.2	S DZ	INCO[9]
Mn Bronze A	675	S	751	5640	2.6	V S DZ	INCO[9]
Mn Bronze A	675	W	1064	5300	2.0	S DZ	INCO[9]
Mn Bronze A	675	S	1064	5300	1.2	S DZ	INCO[9]
Mn Bronze A	675	W	197	2340	1.2	S DZ	INCO[9]
Mn Bronze A	675	S	197	2340	0.2	SL DZ	INCO[9]
Mn Bronze A	675	W	402	2370	0.8	S DZ	INCO[9]
Mn Bronze A	675	S	402	2370	<0.1	SL DZ	INCO[9]
Mn Bronze A	675	W	181	5	4.8	S DZ	INCO[9]

Table 7. Corrosion Rates and Types of Corrosion of Copper-Zinc Alloys (Brasses) (cont'd)

Alloy	CDA No.[1]	Environment[2]	Exposure, Days	Depth, Feet	Corrosion Rate, MPY	Type of[4] Corrosion	Source[3]
Ni-Mn Bronze[6]	-	W	123	5640	0.5	SL DZ	NCEL
Ni-Mn Bronze	-	W	403	6780	0.4	MD DZ	NCEL
Ni-Mn Bronze	-	S	403	6780	0.5	MD DZ	NCEL
Ni-Mn Bronze	-	W	751	5640	2.3	V S DZ	NCEL
Ni-Mn Bronze	-	W	197	2340	0.4	SL DZ	NCEL
Ni-Mn Bronze	-	S	197	2340	0.4	SL DZ	NCEL
Ni-Mn Bronze	-	W	402	2340	1.6	SL DZ	NCEL
Ni-Mn Bronze	-	S	402	2340	2.9	SL DZ	NCEL
Ni-Mn Bronze	-	W	181	5	<0.1	SL DZ	NCEL
Al Brass	-	W	123	5640	0.7	U	INCO[9]
Al Brass	-	S	123	5640	0.5	U	INCO[9]
Al Brass	-	W	403	6780	0.4	U	INCO[9]
Al Brass	-	S	403	6780	0.1	GBSL	INCO[9]
Al Brass	-	W	751	5640	0.3	U	INCO[9]
Al Brass	-	S	751	5640	0.1	U	INCO[9]
Al Brass	-	W	1064	5300	0.2	U	INCO[9]
Al Brass	-	S	1064	5300	0.8	G	INCO[9]
Al Brass	-	W	197	2340	0.5	U	INCO[9]
Al Brass	-	S	197	2340	<0.1	U	INCO[9]
Al Brass	-	W	402	2370	0.3	U	INCO[9]
Al Brass	-	S	402	2370	0.1	ET	INCO[9]
Al Brass	-	W	181	5	0.8	G	INCO[9]
Ni-Brass	-	W	123	5640	1.3	U	INCO[9]
Ni-Brass	-	S	123	5640	1.1	U	INCO[9]
Ni-Brass	-	W	403	6780	1.3	U	INCO[9]
Ni-Brass	-	S	403	6780	0.2	GBSL	INCO[9]

Table 7. Corrosion Rates and Types of Corrosion of Copper-Zinc Alloys (Brasses) (cont'd)

Alloy	CDA No.[1]	Environment[2]	Exposure, Days	Depth, Feet	Corrosion Rate, MPY	Type of[4] Corrosion	Source[3]
Ni-Brass	-	W	751	5640	1.0	U	INCO[9]
Ni-Brass	-	S	751	5640	0.7	U	INCO[9]
Ni-Brass	-	W	1064	5300	0.8	U	INCO[9]
Ni-Brass	-	S	1064	5300	0.5	U	INCO[9]
Ni-Brass	-	W	197	2340	0.8	U	INCO[9]
Ni-Brass	-	S	197	2340	<0.1	NU ET	INCO[9]
Ni-Brass	-	W	402	2370	0.7	U	INCO[9]
Ni-Brass	-	S	402	2370	<0.1	ET	INCO[9]
Ni-Brass	-	W	181	5	1.1	U	INCO[9]

[1] Copper Development Association alloy number

[2] W - Totally exposed in sea water on sides of structure
S - Exposed in base of structure so that the lower portions of the specimens were embedded in the bottom sediments

[3] Numbers refer to references at end of paper

[4] Symbols for types of corrosion
C - Crevice
DZ - Dezincification
ET - Etching
EX - Extensive
G - General
GBSL - General below sediment line

Table 7. Corrosion Rates and Types of Corrosion of Copper-Zinc Alloys (Brasses) (cont'd)

4/ Symbols for types of corrosion (cont'd)

MD - Medium
MO - Moderate
NU - Non-uniform
P - Pitting
S - Severe
SL - Slight
U - Uniform
V - Very
Numbers indicate mils
i.e. 20 - 20 mils
20m - 20 mils maximum
14.6a - 14.6 mils average

5/ At spacer

6/ Cast alloy

Table 8. Stress Corrosion of Copper-Zinc Alloys (Brasses)

Alloy	CDA No.1/	Stress, KSI	Tensile Strength, o/o	Exposure		Specimens	
				Days	Depth, Feet	Exposed	Failed
Arsenical Admiralty	443	10.0	50	403	6780	2	0
Arsenical Admiralty	443	14.0	75	403	6780	2	0
Arsenical Admiralty	443	9.5	50	197	2340	3	0
Arsenical Admiralty	443	14.3	75	197	2340	3	0
Arsenical Admiralty	443	9.0	50	402	2370	3	0
Arsenical Admiralty	443	13.4	75	402	2370	3	0
Muntz Metal	280	12.0	50	403	6780	2	0
Muntz Metal	280	18.0	75	403	6780	2	0
Muntz Metal	280	12.2	50	197	2340	3	0
Muntz Metal	280	18.3	75	197	2340	3	0
Muntz Metal	280	17.7	50	402	2370	3	0
Muntz Metal	280	26.5	75	402	2370	3	0

1/ Copper Development Association alloy number

Table 9. Changes in Mechanical Properties of Copper-Zinc Alloys (Brasses) Due to Corrosion

Alloy	CDA No.[1/]	Exposure		Original Properties			Percent Change		
		Days	Depth, Feet	Tensile Strength, KSI	Yield Strength, KSI	Elongation Percent	Tensile Strength	Yield Strength	Elongation
Arsenical Admiralty	443	-	-	50.9	19.0	66.0	-	-	-
Arsenical Admiralty	443	123	5640	-	-	-	-0.4	+3.2	-2.0
Arsenical Admiralty	443	403	6780	-	-	-	-1.8	-4.5	+0.6
Arsenical Admiralty	443	751	5640	-	-	-	-1.7	-0.6	+1.2
Arsenical Admiralty	443	197	2340	-	-	-	-6.1	-20.5	-3.0
Arsenical Admiralty	443	402	2370	-	-	-	-2.1	-2.6	-1.4
Muntz Metal	280	-	-	55.5	24.4	52.8	-	-	-
Muntz Metal	280	123	5640	-	-	-	-3.8	-3.3	-5.9
Muntz Metal	280	403	6780	-	-	-	-16.0	-11.5	-24.8
Muntz Metal	280	751	5640	-	-	-	-31.5	-29.1	-30.5
Muntz Metal	280	197	2340	-	-	-	-6.2	-16.7	-5.8
Muntz Metal	280	402	2370	-	-	-	-8.1	-10.2	-15.0
Ni-Mn Bronze[2/]	-	-	-	70.6	31.0	20.0	-	-	-
Ni-Mn Bronze[2/]	-	123	5640	-	-	-	-1.8	-10.0	+25.0
Ni-Mn Bronze[2/]	-	403	6780	-	-	-	-33.4	-7.6	-60.0
Ni-Mn Bronze[2/]	-	751	5640	-	-	-	-39.8	-20.9	-57.5
Ni-Mn Bronze[2/]	-	197	2340	-	-	-	-3.4	-16.6	+15.8
Ni-Mn Bronze[2/]	-	402	2370	-	-	-	-6.0	+53.2	-60.5

1/ Copper Development Association alloy number

2/ Cast alloy

Table 10. Chemical Composition of Copper Alloys (Bronzes), Percent by Weight

Alloy	CDA No. 1/	Cu	Sn	Zn	Ni	Al	Fe	Si	Pb	P	Mn	Source 2/
G Bronze 3/	-	88.0	2.0	10.0	-	-	-	-	-	-	-	INCO 9/
Modified G Bronze 3/	-	88.0	8.0	4.0	-	-	-	-	-	-	-	INCO 9/
M Bronze 3/	-	88.2	6.0	4.0	-	-	-	-	2.0	-	-	INCO 9/
Leaded Sn Bronze 3/	-	85.0	5.0	5.0	-	-	-	-	5.0	-	-	INCO 9/
Phosphor Bronze A	510	94.64	4.94	<0.10	-	-	<0.05	-	-	0.26	-	NCEL
Phosphor Bronze A	510	96.0	4.0	-	-	-	-	-	-	0.25	-	INCO 9/
Phosphor Bronze A	510	95.62	4.44	<0.10	-	-	<0.05	-	-	0.06	-	NCEL 11/
Phosphor Bronze D	524	90.00	9.23	<0.10	-	-	<0.05	-	-	0.17	-	NCEL
Al Bronze	606	95.0	-	-	-	5.0	-	-	-	-	-	INCO 9/
Al Bronze	606	95.11	-	-	-	4.76	<0.05	-	-	-	-	NCEL 11/
Al Bronze D	614	90.11	-	0.15	-	6.59	3.15	-	<0.02	-	-	NCEL
Al Bronze, 7% 3/	614	90.0	-	-	-	7.0	3.0	-	-	-	-	INCO 9/
Al Bronze, 10% 3/	-	89.0	-	-	-	10.0	1.0	-	-	-	-	INCO 9/
Al Bronze, 11% 3/	-	86.0	-	-	-	10.0	4.0	-	-	-	-	INCO 9/
Al Bronze, 13% 3/	-	83.0	-	-	-	13.0	4.0	-	-	-	-	INCO 9/
Ni-Al Bronze #1	-	80.0	-	-	4.0	11.0	4.0	-	-	-	1.0	INCO 9/
Ni-Al Bronze #2	-	80.0	-	-	5.0	10.0	4.0	-	-	-	0.5	INCO 9/
Ni-Al Bronze #3	-	80.0	-	-	5.0	9.0	3.5	-	-	-	3.0	INCO 9/
Si Bronze, 3%	653	97.0	-	-	-	-	-	3.0	-	-	-	INCO 9/
Si Bronze A	655	95.49	-	-	-	-	<0.02	3.28	-	-	1.18	NCEL
Si Bronze A	655	95.0	-	-	-	-	-	3.0	-	-	1.0	INCO 9/
Ni-Vee Bronze A 3/	-	88.0	5.0	2.0	5.0	-	-	-	-	-	-	INCO 9/
Ni-Vee Bronze B 3/	-	87.0	5.0	2.0	5.0	-	-	1.0	-	-	-	INCO 9/
Ni-Vee Bronze C 3/	-	80.0	5.0	5.0	5.0	-	-	5.0	-	-	-	INCO 9/

1/ Copper Development Association alloy number
2/ Numbers refer to references at end of paper
3/ Cast alloy

Table 11. Corrosion Rates and Types of Corrosion of Copper Alloys (Bronzes)

Alloy	CDA No.[1]	Environment[2]	Exposure, Days	Depth, Feet	Corrosion Rate, MPY	Type of[4] Corrosion	Source[3]
G Bronze[5]	-	W	123	5640	0.5	U	INCO[9]
G Bronze	-	S	123	5640	0.3	U	INCO[9]
G Bronze	-	W	403	6780	0.7	U	INCO[9]
G Bronze	-	S	403	6780	0.1	GBSL	INCO[9]
G Bronze	-	W	751	5640	0.7	U	INCO[9]
G Bronze	-	S	751	5640	0.3	U	INCO[9]
G Bronze	-	W	1064	5300	0.3	U	INCO[9]
G Bronze	-	S	1064	5300	0.4	U	INCO[9]
G Bronze	-	W	197	2340	0.2	U	INCO[9]
G Bronze	-	S	197	2340	<0.1	I C	INCO[9]
G Bronze	-	W	402	2370	0.3	U	INCO[9]
G Bronze	-	S	402	2370	<0.1	ET	INCO[9]
G Bronze	-	W	181	5	1.3	G	INCO[9]
Modified G Bronze[5]	-	W	123	5640	0.5	U	INCO[9]
Modified G Bronze	-	S	123	5640	0.3	U	INCO[9]
Modified G Bronze	-	W	403	6780	0.4	U	INCO[9]
Modified G Bronze	-	S	403	6780	<0.1	U	INCO[9]
Modified G Bronze	-	W	751	5640	0.7	U	INCO[9]
Modified G Bronze	-	S	751	5640	0.4	C, 19	INCO[9]
Modified G Bronze	-	W	1064	5300	0.4	C, 18; P	INCO[9]
Modified G Bronze	-	S	1064	5300	0.5	U	INCO[9]
Modified G Bronze	-	W	197	2340	0.3	U	INCO[9]
Modified G Bronze	-	S	197	2340	0.2	NU ET	INCO[9]
Modified G Bronze	-	W	402	2370	0.3	U	INCO[9]
Modified G Bronze	-	S	402	2370	<0.1	ET	INCO[9]
Modified G Bronze	-	W	181	5	1.3	G	INCO[9]

Table 11. Corrosion Rates and Types of Corrosion of Copper Alloys (Bronzes) (cont'd)

Alloy	CDA No.[1]	Environ-[2] ment	Exposure, Days	Depth, Feet	Corrosion Rate, MPY	Type of[4] Corrosion	Source[3]
M Bronze[5]	-	W	123	5640	0.5	U	INCO[9]
M Bronze	-	S	123	5640	0.4	U	INCO[9]
M Bronze	-	W	403	6780	0.4	U	INCO[9]
M Bronze	-	S	403	6780	<0.1	U	INCO[9]
M Bronze	-	W	751	5640	0.7	U	INCO[9]
M Bronze	-	S	751	5640	0.3	U	INCO[9]
M Bronze	-	W	1064	5300	0.4	U	INCO[9]
M Bronze	-	S	1064	5300	0.4	U	INCO[9]
M Bronze	-	W	197	2340	0.4	U	INCO[9]
M Bronze	-	S	197	2340	0.1	ET	INCO[9]
M Bronze	-	W	402	2370	0.3	U	INCO[9]
M Bronze	-	S	402	2370	<0.1	ET	INCO[9]
M Bronze	-	W	181	5	1.6	G	INCO[9]
Leaded Sn Bronze[5]	-	W	123	5640	0.4	U	INCO[9]
Leaded Sn Bronze	-	S	123	5640	0.2	U	INCO[9]
Leaded Sn Bronze	-	W	403	6780	0.5	U	INCO[9]
Leaded Sn Bronze	-	S	403	6780	0.1	U	INCO[9]
Leaded Sn Bronze	-	W	751	5640	0.6	U	INCO[9]
Leaded Sn Bronze	-	S	751	5640	3.2	S G	INCO[9]
Leaded Sn Bronze	-	W	1064	5300	0.4	U	INCO[9]
Leaded Sn Bronze	-	S	1064	5300	0.3	U	INCO[9]
Leaded Sn Bronze	-	W	197	2340	0.5	U	INCO[9]
Leaded Sn Bronze	-	S	197	2340	<0.1	NU ET	INCO[9]
Leaded Sn Bronze	-	W	402	2370	0.5	U	INCO[9]
Leaded Sn Bronze	-	S	402	2370	<0.1	ET	INCO[9]
Leaded Sn Bronze	-	W	181	5	1.4	G	INCO[9]

Table 11. Corrosion Rates and Types of Corrosion of Copper Alloys (Bronzes) (cont'd)

Alloy	CDA No.[1]	Environment[2]	Exposure, Days	Depth, Feet	Corrosion Rate, MPY	Type of[4] Corrosion	Source[3]
P Bronze A	510	W	123	5640	0.6	U	NCEL
P Bronze A	510	W	123	5640	0.5	U	INCO[9]
P Bronze A	510	S	123	5640	0.4	U	NCEL
P Bronze A	510	S	123	5640	0.4	U	INCO[9]
P Bronze A	510	W	403	6780	0.2	ET	NCEL
P Bronze A	510	W	403	6780	0.3	U	INCO[9]
P Bronze A	510	S	403	6780	0.3	ET	NCEL
P Bronze A	510	S	403	6780	0.1	GBSL	INCO[9]
P Bronze A	510	W	751	5640	0.2	ET	NCEL
P Bronze A	510	W	751	5640	0.3	U	INCO[9]
P Bronze A	510	S	751	5640	0.1	U	INCO[9]
P Bronze A	510	W	1064	5300	0.4	U	NCEL[11]
P Bronze A	510	W	1064	5300	0.2	U	INCO[9]
P Bronze A	510	S	1064	5300	0.4	G	INCO[9]
P Bronze A	510	W	197	2340	0.3	U	NCEL
P Bronze A	510	W	197	2340	0.4	U	INCO[9]
P Bronze A	510	S	197	2340	0.3	[6]	NCEL
P Bronze A	510	S	197	2340	<0.1	I C	INCO[9]
P Bronze A	510	W	402	2370	0.1	ET	NCEL
P Bronze A	510	W	402	2370	0.2	U	INCO[9]
P Bronze A	510	S	402	2370	0.2	EWO	NCEL
P Bronze A	510	S	402	2370	0.2	ET	INCO[9]
P Bronze A	510	W	181	5	1.1	U	NCEL
P Bronze A	510	W	181	5	1.6	P, 4	INCO[9]
P Bronze D	524	W	123	5640	0.5	U	NCEL
P Bronze D	524	S	123	5640	0.4	U	NCEL
P Bronze D	524	W	403	6780	0.2	ET	NCEL

Table 11. Corrosion Rates and Types of Corrosion of Copper Alloys (Bronzes) (cont'd)

Alloy	CDA No.[1]	Environment[2]	Exposure, Days	Depth, Feet	Corrosion Rate, MPY	Type of[4] Corrosion	Source[3]
P Bronze D	524	S	403	6780	0.3	ET	NCEL
P Bronze D	524	W	751	5640	0.3	U	NCEL
P Bronze D	524	S	751	5640	0.4	NU	NCEL
P Bronze D	524	W	197	2340	0.4	U	NCEL
P Bronze D	524	S	197	2340	0.2	U	NCEL
P Bronze D	524	W	402	2370	<0.1	U	NCEL
P Bronze D	524	S	402	2370	<0.1	U	NCEL
P Bronze D	524	W	181	5	1.1	NU	NCEL
Al Bronze, 5%	606	W	123	5640	0.6	U	INCO[9]
Al Bronze, 5%	606	S	123	5640	0.4	U	INCO[9]
Al Bronze, 5%	606	W	403	6780	0.2	SL DA	INCO[9]
Al Bronze, 5%	606	S	403	6780	<0.1	U	INCO[9]
Al Bronze, 5%	606	W	751	5640	0.3	SL DA	INCO[9]
Al Bronze, 5%	606	S	751	5640	0.2	V SL DA	INCO[9]
Al Bronze, 5%	606	W	1064	5300	0.2	NU	NCEL[11]
Al Bronze, 5%	606	W	1064	5300	0.2	CR, 5	INCO[9]
Al Bronze, 5%	606	S	1064	5300	0.5	G	INCO[9]
Al Bronze, 5%	606	W	197	2340	0.4	U	INCO[9]
Al Bronze, 5%	606	S	197	2340	0.2	NU ET	INCO[9]
Al Bronze, 5%	606	W	402	2370	0.2	U	INCO[9]
Al Bronze, 5%	606	S	402	2370	0.1	ET	INCO[9]
Al Bronze, 5%	606	W	181	5	1.1	G	INCO[9]
Al Bronze, 7%	614	W	123	5640	0.5	SL DA	NCEL
Al Bronze, 7%	614	W	123	5640	0.6	U	INCO[9]
Al Bronze, 7%	614	S	123	5640	0.3	U	NCEL
Al Bronze, 7%	614	S	123	5640	0.4	U	INCO[9]

Table 11. Corrosion Rates and Types of Corrosion of Copper Alloys (Bronzes) (cont'd)

Alloy	CDA No.[1]	Environment[2]	Exposure, Days	Depth, Feet	Corrosion Rate, MPY	Type of[4] Corrosion	Source[3]
Al Bronze, 7%	614	W	403	6780	0.7	SL DA; C, 12; P, 12m, 6.6a	NCEL
Al Bronze, 7%	614	W	403	6780	0.2	U	INCO[9]
Al Bronze, 7%	614	S	403	6780	0.7	SL DA; C, 13; P, 16m, 10a	NCEL
Al Bronze, 7%	614	S	403	6780	<0.1	SL DA	INCO[9]
Al Bronze, 7%	614	W	751	5640	0.5	MD DA; C, 7; P, 12m, 7.9a	NCEL
Al Bronze, 7%	614	W	751	5640	1.5	G	INCO[9]
Al Bronze, 7%	614	S	751	5640	0.2	V SL DA	INCO[9]
Al Bronze, 7%	614	W	1064	5300	0.2	CR, 7	INCO[9]
Al Bronze, 7%	614	S	1064	5300	0.2	MO DA	INCO[9]
Al Bronze, 7%	614	W	197	2340	0.3	U	NCEL
Al Bronze, 7%	614	W	197	2340	0.3	U	INCO[9]
Al Bronze, 7%	614	S	197	2340	0.1	U	NCEL
Al Bronze, 7%	614	S	197	2340	0.2	ET	INCO[9]
Al Bronze, 7%	614	W	402	2370	0.2	U	NCEL
Al Bronze, 7%	614	W	402	2370	0.2	ET	INCO[9]
Al Bronze, 7%	614	S	402	2370	0.2	U	INCO[9]
Al Bronze, 7%	614	S	402	2370	0.1	SL DA	INCO[9]
Al Bronze, 7%	614	W	181	5	2.9	NU DA	NCEL
Al Bronze, 7%	614	W	181	5	0.8	G	INCO[9]
Al Bronze, 10%[5]	-	W	123	5640	0.7	SL DA	INCO[9]
Al Bronze, 10%	-	S	123	5640	0.6	SL DA	INCO[9]
Al Bronze, 10%	-	W	403	6780	0.7	MO DA	INCO[9]
Al Bronze, 10%	-	S	403	6780	<0.1	SL DA	INCO[9]
Al Bronze, 10%	-	W	751	5640	2.3	G	INCO[9]
Al Bronze, 10%	-	S	751	5640	0.9	U SL DA	INCO[9]

Table 11. Corrosion Rates and Types of Corrosion of Copper Alloys (Bronzes) (cont'd)

Alloy	CDA No.[1]	Environ-ment[2]	Exposure, Days	Depth, Feet	Corrosion Rate, MPY	Type of[4] Corrosion	Source[3]
Al Bronze, 10%	-	W	1064	5300	0.2	U	INCO[9]
Al Bronze, 10%	-	S	1064	5300	0.4	SL DA	INCO[9]
Al Bronze, 10%	-	W	197	2340	0.3	MO DA	INCO[9]
Al Bronze, 10%	-	S	197	2340	0.2	MO DA	INCO[9]
Al Bronze, 10%	-	W	402	2370	0.3	S DA	INCO[9]
Al Bronze, 10%	-	S	402	2370	<0.1	MO DA	INCO[9]
Al Bronze, 10%	-	W	181	5	2.1	MO DA	INCO[9]
Al Bronze, 11%[5]	-	W	123	5640	0.5	V SL DA	INCO[9]
Al Bronze, 11%	-	S	123	5640	0.4	V SL DA	INCO[9]
Al Bronze, 11%	-	W	403	6780	0.1	SL DA	INCO[9]
Al Bronze, 11%	-	S	403	6780	<0.1	SL DA	INCO[9]
Al Bronze, 11%	-	W	751	5640	0.8	SL DA	INCO[9]
Al Bronze, 11%	-	S	751	5640	0.1	V SL DA	INCO[9]
Al Bronze, 11%	-	W	1064	5300	0.1	SL DA	INCO[9]
Al Bronze, 11%	-	S	1064	5300	0.2	MO DA	INCO[9]
Al Bronze, 11%	-	W	197	2340	0.2	SL DA[7]	INCO[9]
Al Bronze, 11%	-	S	197	2340	<0.1	SL DA[8]	INCO[9]
Al Bronze, 11%	-	W	402	2370	0.2	MO DA	INCO[9]
Al Bronze, 11%	-	S	402	2370	<0.1	SL DA	INCO[9]
Al Bronze, 13%[5]	-	W	123	5640	0.5	V SL DA	INCO[9]
Al Bronze, 13%	-	S	123	5640	0.5	V SL DA	INCO[9]
Al Bronze, 13%	-	W	403	6780	0.6	S DA	INCO[9]
Al Bronze, 13%	-	S	403	6780	<0.1	SL DA	INCO[9]
Al Bronze, 13%	-	W	751	5640	1.9	S DA	INCO[9]
Al Bronze, 13%	-	S	751	5640	0.5	MO DA	INCO[9]
Al Bronze, 13%	-	W	1064	5300	0.6	S DA	INCO[9]

Table 11. Corrosion Rates and Types of Corrosion of Copper Alloys (Bronzes) (cont'd)

Alloy	CDA No.[1]	Environ-ment[2]	Exposure, Days	Depth, Feet	Corrosion Rate, MPY	Type of[4] Corrosion	Source[3]
Al Bronze, 13%	-	S	1064	5300	0.3	SL DA	INCO[9]
Al Bronze, 13%	-	W	197	2340	0.4	MO DA	INCO[9]
Al Bronze, 13%	-	S	197	2340	<0.1	SL DA	INCO[9]
Al Bronze, 13%	-	W	402	2370	0.3	MO DA	INCO[9]
Al Bronze, 13%	-	S	402	2370	<0.1	SL DA	INCO[9]
Al Bronze, 13%	-	W	181				
Ni-Al Bronze,#1	-	W	123	5640	0.4	I P	INCO[9]
Ni-Al Bronze,#1	-	S	123	5640	0.2	I P	INCO[9]
Ni-Al Bronze,#1	-	W	403	6780	0.3	I P	INCO[9]
Ni-Al Bronze,#1	-	S	403	6780	0.1	U	INCO[9]
Ni-Al Bronze,#1	-	W	751	5640	1.1	C, 16; P	INCO[9]
Ni-Al Bronze,#1	-	S	751	5640	0.3	P, 17	INCO[9]
Ni-Al Bronze,#1	-	W	1064	5300	0.1	P, 8	INCO[9]
Ni-Al Bronze,#1	-	S	1064	5300	1.2	CR, 30	INCO[9]
Ni-Al Bronze,#1	-	W	197	2340	0.3	U	INCO[9]
Ni-Al Bronze,#1	-	S	197	2340	<0.1	U ET	INCO[9]
Ni-Al Bronze, #2	-	W	123	5640	0.5	U	INCO[9]
Ni-Al Bronze, #2	-	S	123	5640	0.3	U	INCO[9]
Ni-Al Bronze, #2	-	W	403	6780	0.2	I P	INCO[9]
Ni-Al Bronze, #2	-	S	403	6780	0.1	U	INCO[9]
Ni-Al Bronze, #2	-	W	751	5640	0.5	SL DA	INCO[9]
Ni-Al Bronze, #2	-	S	751	5640	0.2	C, 13	INCO[9]
Ni-Al Bronze, #2	-	W	1064	5300	0.2	C, 5	INCO[9]
Ni-Al Bronze, #2	-	S	1064	5300	0.5	CR, 21	INCO[9]
Ni-Al Bronze, #2	-	W	197	2340	0.3	U	INCO[9]
Ni-Al Bronze, #2	-	S	197	2340	0.1	U	INCO[9]

Table 11. Corrosion Rates and Types of Corrosion of Copper Alloys (Bronzes) (cont'd)

Alloy	CDA No.[1]	Environment[2]	Exposure, Days	Depth, Feet	Corrosion Rate, MPY	Type of[4] Corrosion	Source[3]
Ni-Al Bronze, #2	-	W	402	2370	0.2	U	INCO[9]
Ni-Al Bronze, #2	-	S	402	2370	<0.1	ET	INCO[9]
Ni-Al Bronze, #2	-	W	181	5	1.0	C, 8	INCO[9]
Ni-Al Bronze, #3	-	W	123	5640	0.4	U	INCO[9]
Ni-Al Bronze, #3	-	S	123	5640	0.3	U	INCO[9]
Ni-Al Bronze, #3	-	W	403	6780	0.2	U	INCO[9]
Ni-Al Bronze, #3	-	S	403	6780	<0.1	NU ET	INCO[9]
Ni-Al Bronze, #3	-	W	751	5640	0.2	I P	INCO[9]
Ni-Al Bronze, #3	-	S	751	5640	0.1	U	INCO[9]
Ni-Al Bronze, #3	-	W	1064	5300	<0.1	P, 4	INCO[9]
Ni-Al Bronze, #3	-	S	1064	5300	0.2	CR, 10	INCO[9]
Ni-Al Bronze, #3	-	W	197	2340	0.3	U	INCO[9]
Ni-Al Bronze, #3	-	S	197	2340	0.2	U	INCO[9]
Si Bronze, 3%	653	W	123	5640	1.3	U	INCO[9]
Si Bronze, 3%	653	S	123	5640	1.5	U	INCO[9]
Si Bronze, 3%	653	W	403	6780	1.2	MO CO	INCO[9]
Si Bronze, 3%	653	S	403	6780	0.4	GBSL	INCO[9]
Si Bronze, 3%	653	W	751	5640	1.0	U	INCO[9]
Si Bronze, 3%	653	S	751	5640	0.7	U	INCO[9]
Si Bronze, 3%	653	W	1064	5300	0.6	MO CO	INCO[9]
Si Bronze, 3%	653	S	1064	5300	0.4	SL CO	INCO[9]
Si Bronze, 3%	653	W	197	2340	1.1	U	INCO[9]
Si Bronze, 3%	653	S	197	2340	0.1	NU ET	INCO[9]
Si Bronze, 3%	653	W	402	2370	1.2	U	INCO[9]
Si Bronze, 3%	653	S	402	2370	0.2	ET	INCO[9]
Si Bronze, 3%	653	W	181	5	1.7	U	INCO[9]

Table 11. Corrosion Rates and Types of Corrosion of Copper Alloys (Bronzes) (cont'd)

Alloy	CDA No.[1]	Environment[2]	Exposure, Days	Depth, Feet	Corrosion Rate, MPY	Type of[4] Corrosion	Source[3]
Si Bronze A	655	W	123	5640	1.6	U	NCEL[9]
Si Bronze A	655	W	123	5640	1.4	U	INCO[9]
Si Bronze A	655	S	123	5640	1.8	U	NCEL[9]
Si Bronze A	655	S	123	5640	1.5	U	INCO[9]
Si Bronze A	655	W	403	6780	1.2	U	NCEL[9]
Si Bronze A	655	W	403	6780	1.2	U	INCO[9]
Si Bronze A	655	S	403	6780	1.8	ET	NCEL[9]
Si Bronze A	655	S	403	6780	0.2	GBSL	INCO[9]
Si Bronze A	655	W	751	5640	0.8	S CO	NCEL[9]
Si Bronze A	655	W	751	5640	1.4	U	INCO[9]
Si Bronze A	655	S	751	5640	0.9	G	INCO[9]
Si Bronze A	655	W	1064	5300	0.6	SL CO	INCO[9]
Si Bronze A	655	S	1064	5300	0.4	U	INCO[9]
Si Bronze A	655	W	197	2340	0.9	U	NCEL[9]
Si Bronze A	655	W	197	2340	1.1	U	INCO[9]
Si Bronze A	655	S	197	2340	0.6	U	NCEL[9]
Si Bronze A	655	S	197	2340	0.2	U	INCO[9]
Si Bronze A	655	W	402	2370	1.0	ET	NCEL[9]
Si Bronze A	655	W	402	2370	0.8	U	INCO[9]
Si Bronze A	655	S	402	2370	0.8	ET	NCEL[9]
Si Bronze A	655	S	402	2370	0.1	ET	INCO[9]
Si Bronze A	655	W	181	5	1.8	U	NCEL[9]
Si Bronze A	655	W	181	5	1.6	G	INCO[9]
Ni-Vee Bronze A[5]	-	W	123	5640	0.7	U	INCO[9]
Ni-Vee Bronze A	-	S	123	5640	0.5	U	INCO[9]
Ni-Vee Bronze A	-	W	403	6780	0.6	U	INCO[9]

Table 11. Corrosion Rates and Types of Corrosion of Copper Alloys (Bronzes) (cont'd)

Alloy	CDA No.[1]	Environment[2]	Exposure, Days	Depth, Feet	Corrosion Rate, MPY	Type of[4] Corrosion	Source[3]
Ni-Vee Bronze A	-	S	403	6780	0.3	U	INCO[9]
Ni-Vee Bronze A	-	W	751	5640	2.6	S[9]	INCO[9]
Ni-Vee Bronze A	-	S	751	5640	0.4	U	INCO[9]
Ni-Vee Bronze A	-	W	1064	5300	2.2	CR, 20	INCO[9]
Ni-Vee Bronze A	-	S	1064	5300	0.3	U	INCO[9]
Ni-Vee Bronze A	-	W	197	2340	0.6	U	INCO[9]
Ni-Vee Bronze A	-	S	197	2340	<0.1	NU ET	INCO[9]
Ni-Vee Bronze A	-	W	402	2370	0.4	U	INCO[9]
Ni-Vee Bronze A	-	S	402	2370	<0.1	ET	INCO[9]
Ni-Vee Bronze A	-	W	181	5	2.0	P, 7	INCO[9]
Ni-Vee Bronze B[5]	-	W	123	5640	0.6	U	INCO[9]
Ni-Vee Bronze B	-	S	123	5640	0.4	U	INCO[9]
Ni-Vee Bronze B	-	W	403	6780	0.5	U	INCO[9]
Ni-Vee Bronze B	-	S	403	6780	0.1	U	INCO[9]
Ni-Vee Bronze B	-	W	751	5640	0.5	U	INCO[9]
Ni-Vee Bronze B	-	S	751	5640	0.3	U	INCO[9]
Ni-Vee Bronze B	-	W	1064	5300	0.3	U	INCO[9]
Ni-Vee Bronze B	-	S	1064	5300	0.4	U	INCO[9]
Ni-Vee Bronze B	-	W	197	2340	0.6	U	INCO[9]
Ni-Vee Bronze B	-	S	197	2340	<0.1	NU ET	INCO[9]
Ni-Vee Bronze B	-	W	402	2370	1.2	U	INCO[9]
Ni-Vee Bronze B	-	S	402	2370	<0.1	ET	INCO[9]
Ni-Vee Bronze B	-	W	181	5	1.8	P, 4	INCO[9]
Ni-Vee Bronze C[5]	-	W	123	5640	0.8	U	INCO[9]
Ni-Vee Bronze C	-	S	123	5640	0.5	U	INCO[9]
Ni-Vee Bronze C	-	W	403	6780	0.8	U	INCO[9]

Table 11. Corrosion Rates and Types of Corrosion of Copper Alloys (Bronzes) (cont'd)

Alloy	CDA No.[1]	Environment[2]	Exposure, Days	Depth, Feet	Corrosion Rate, MPY	Type of[4] Corrosion	Source[3]
Ni-Vee Bronze C	-	S	403	6780	0.2	U	INCO[9]
Ni-Vee Bronze C	-	W	751	5640	2.0	G	INCO[9]
Ni-Vee Bronze C	-	S	751	5640	0.4	U	INCO[9]
Ni-Vee Bronze C	-	W	1064	5300	0.5	U	INCO[9]
Ni-Vee Bronze C	-	S	1064	5300	0.3	U	INCO[9]
Ni-Vee Bronze C	-	W	197	2340	0.8	U	INCO[9]
Ni-Vee Bronze C	-	S	197	2340	<0.1	ET	INCO[9]
Ni-Vee Bronze C	-	W	402	2370	0.6	U	INCO[9]
Ni-Vee Bronze C	-	S	402	2370	0.1	ET	INCO[9]
Ni-Vee Bronze C	-	W	181	5	1.8	U	INCO[9]

1/ Copper Development Association alloy numbers.

2/ W - Totally exposed in sea water on sides of structure.
S - Exposed in base of structure so that a portion of each specimen was exposed in the bottom sediments.

3/ Numbers refer to references at end of paper.

4/ Symbols for types of corrosion

C - Crevice
CO - Coppering, a selective attack where copper appears on surface similar to dezincification.
CR - Cratering
DA - Dealuminification

Table 11. Corrosion Rates and Types of Corrosion of Copper Alloys (Bronzes) (cont'd)

4/ Symbols for types of corrosion (cont'd)

ET - Etching
EWO - Etched only in the water
G - General
GBSL - General below sediment line
I - Incipient
MD - Medium
MO - Moderate
NU - Non-uniform
P - Pitting
S - Severe
SL - Slight
U - Uniform
V - Very
Numbers indicate mils
i.e. 20 - 20 mils
20m - 20 mils maximum
14.6a - 14.6 mils average

5/ Cast alloy

6/ Pitting in bottom sediment, 12 mils maximum

7/ At spacer

8/ At crevice

9/ In one small area only

Table 12. Stress Corrosion of Copper Alloys (Bronzes)

Alloy	CDA No.[1/]	Stress, KSI	Tensile Strength, %	Exposure		Specimens	
				Days	Depth, Feet	Exposed	Failed
Phosphor Bronze A	510	12.0	50	403	6780	2	0
Phosphor Bronze A	510	19.0	75	403	6780	2	0
Phosphor Bronze A	510	12.5	50	197	2340	3	0
Phosphor Bronze A	510	18.7	75	197	2340	3	0
Phosphor Bronze A	510	12.6	50	402	2370	3	0
Phosphor Bronze A	510	19.0	75	402	2370	3	0
Phosphor Bronze D	524	10.0	35	403	6780	2	0
Phosphor Bronze D	524	14.0	50	403	6780	2	0
Phosphor Bronze D	524	21.0	75	403	6780	2	0
Phosphor Bronze D	524	9.8	35	197	2340	3	0
Phosphor Bronze D	524	13.9	50	197	2340	3	0
Phosphor Bronze D	524	20.9	75	197	2340	3	0
Phosphor Bronze D	524	16.4	50	402	2370	3	0
Phosphor Bronze D	524	24.5	75	402	2370	3	0
Al Bronze	606	18.0	35	403	6780	2	0
Al Bronze	606	26.0	50	403	6780	2	0
Al Bronze	606	38.0	75	403	6780	2	0
Al Bronze	606	17.9	35	197	2340	3	0
Al Bronze	606	25.6	50	197	2340	3	0
Al Bronze	606	38.4	75	197	2340	3	0
Al Bronze	606	28.3	50	402	2370	3	0
Al Bronze	606	42.5	75	402	2370	3	0
Si Bronze A	655	10.0	35	403	6780	2	0
Si Bronze A	655	14.0	50	403	6780	2	0

Table 12. Stress Corrosion of Copper Alloys (Bronzes) (cont'd)

Alloy	CDA No.[1/]	Stress, KSI	Tensile Strength, %	Exposure		Specimens	
				Days	Depth, Feet	Exposed	Failed
Si Bronze A	655	21.0	75	403	6780	2	0
Si Bronze A	655	9.6	35	197	2340	3	0
Si Bronze A	655	13.8	50	197	2340	3	0
Si Bronze A	655	20.6	75	197	2340	3	0
Si Bronze A	655	10.8	50	402	2370	3	0
Si Bronze A	655	16.2	75	402	2370	3	0

[1/] Copper Development Association alloy number

Table 13. Changes in Mechanical Properties of Copper Alloys (Bronzes) Due to Corrosion

Alloy	CDA No.[1/]	Exposure		Original Properties			Percent Change		
		Days	Depth, Feet	Tensile Strength, KSI	Yield Strength, KSI	Elongation Percent	Tensile Strength	Yield Strength	Elongation
Phosphor Bronze A	510	-	-	51.3	25.0	64.2	-	-	-
Phosphor Bronze A	510	123	5640	-	-	-	0.0	-2.8	+3.3
Phosphor Bronze A	510	403	6780	-	-	-	+1.0	-1.2	+2.1
Phosphor Bronze A	510	751	5640	-	-	-	+1.3	-0.8	-0.6
Phosphor Bronze A	510	197	2340	-	-	-	-3.2	-12.8	-0.9
Phosphor Bronze A	510	402	2370	-	-	-	-0.6	-3.0	-3.2
Phosphor Bronze D	524	-	-	63.9	27.9	69.8	-	-	-
Phosphor Bronze D	524	123	5640	-	-	-	+0.6	0.0	0.0
Phosphor Bronze D	524	403	6780	-	-	-	+1.5	+0.9	+3.3
Phosphor Bronze D	524	751	5640	-	-	-	+1.8	+2.5	-1.4
Phosphor Bronze D	524	197	2340	-	-	-	0.0	-3.3	+2.6
Phosphor Bronze D	524	402	2370	-	-	-	+0.5	+1.4	-0.8
Al Bronze	606	-	-	84.6	51.2	45.0	-	-	-
Al Bronze	606	123	5640	-	-	-	+0.2	+2.0	-8.5
Al Bronze	606	403	6780	-	-	-	-1.4	+0.4	-28.8
Al Bronze	606	751	5640	-	-	-	-0.4	+0.8	-27.4
Al Bronze	606	197	2340	-	-	-	+0.3	-1.8	-7.4
Al Bronze	606	402	2370	-	-	-	-0.2	-0.3	-12.4
Si Bronze A	655	-	-	64.4	27.5	61.3	-	-	-
Si Bronze A	655	123	5640	-	-	-	+1.7	+4.0	-2.4
Si Bronze A	655	403	6780W	-	-	-	-0.6	-4.4	-1.3
Si Bronze A	655	403	6780S	-	-	-	-25.3	-18.2	-39.6
Si Bronze A	655	751	5640	-	-	-	-0.6	-5.1	-1.0
Si Bronze A	655	197	2340	-	-	-	-1.6	-14.0	-3.1
Si Bronze A	655	402	2370	-	-	-	-1.0	-3.0	-2.2

[1/] Copper Development Association alloy number

Table 14. Chemical Composition of Copper-Nickel Alloys, Percent by Weight

Alloy	CDA No.[1]	Cu	Ni	Fe	Mn	Zn	Pb	Source[2]
Cu-Ni, 95-5	704	91.98	6.25	1.24	0.53	-	-	NCEL
Cu-Ni, 90-10	706	89.04	9.42	1.16	0.38	-	-	NCEL
Cu-Ni, 90-10	706	89.0	10.0	1.4	0.5	-	-	INCO[9]
Cu-Ni, 90-10[3]	-	86.0	11.0	1.4	1.3	-	-	INCO[9]
Cu-Ni, 80-20	710	78.62	20.41	0.62	0.35	-	-	NCEL
Cu-Ni, 80-20	-	80.0	20.0	0.03	0.2	-	-	INCO[9]
Cu-Ni, 70-30	715	68.61	30.53	0.53	0.33	-	-	NCEL
Cu-Ni, 70-30	715	69.0	30.0	0.6	0.4	-	-	INCO[9]
Cu-Ni, 70-30	-	64.02	29.95	5.27	0.75	-	-	NCEL
Cu-Ni, 55-45	-	54.0	45.0	0.1	1.0	-	-	INCO[9]
Cu-Ni-Zn-Pb	-	62.0	25.0	-	-	8.0	5.0	INCO[9]
Nickel-Silver	752	65.0	18.0	-	-	17.0	-	INCO[9]

[1] Copper Development Association alloy number

[2] Numbers refer to references at end of paper

[3] Cast alloy

Table 15. Corrosion Rates and Types of Corrosion of Copper-Nickel Alloys

Alloy	CDA No.[1]	Environ-ment[2]	Exposure, Days	Depth, Feet	Corrosion Rate, MPY	Type of[4] Corrosion	Source[3]
Cu-Ni, 95-5	704	W	123	5640	1.5	U	NCEL
Cu-Ni, 95-5	704	S	123	5640	1.5	U	NCEL
Cu-Ni, 95-5	704	W	403	6780	0.8	U	NCEL
Cu-Ni, 95-5	704	S	403	6780	0.8	U	NCEL
Cu-Ni, 95-5	704	W	751	5640	0.7	U	NCEL
Cu-Ni, 95-5	704	S	751	5640	0.6	U	NCEL
Cu-Ni, 95-5	704	W	197	2340	0.9	U	NCEL
Cu-Ni, 95-5	704	S	197	2340	0.6	U	NCEL
Cu-Ni, 95-5	704	W	402	2370	0.9	U	NCEL
Cu-Ni, 95-5	704	S	402	2370	0.8	U	NCEL
Cu-Ni, 90-10	706	W	123	5640	1.6	U	NCEL
Cu-Ni, 90-10	706	W	123	5640	0.8	U	INCO[9]
Cu-Ni, 90-10	706	S	123	5640	1.2	U	NCEL
Cu-Ni, 90-10	706	S	123	5640	0.8	U	INCO[9]
Cu-Ni, 90-10	706	W	403	6780	0.8	U	NCEL
Cu-Ni, 90-10	706	W	403	6780	0.6	U	INCO[9]
Cu-Ni, 90-10	706	S	403	6780	0.7	U	NCEL
Cu-Ni, 90-10	706	S	403	6780	<0.1	U	INCO[9]
Cu-Ni, 90-10	706	W	751	5640	0.7	U	NCEL
Cu-Ni, 90-10	706	W	751	5640	0.6	U	INCO[9]
Cu-Ni, 90-10	706	S	751	5640	0.5	U	INCO[9]
Cu-Ni, 90-10	706	W	1064	5300	0.7	U	INCO[9]
Cu-Ni, 90-10	706	S	1064	5300	0.2	G	INCO[9]
Cu-Ni, 90-10	706	W	197	2340	0.8	U	NCEL
Cu-Ni, 90-10	706	W	197	2340	0.8	U	INCO[9]
Cu-Ni, 90-10	706	S	197	2340	0.5	U	NCEL
Cu-Ni, 90-10	706	S	197	2340	<0.1	U	INCO[9]

Table 15. Corrosion Rates and Types of Corrosion of Copper-Nickel Alloys (cont'd)

Alloy	CDA No.[1/]	Environ-[2/] ment	Exposure, Days	Depth, Feet	Corrosion Rate, MPY	Type of[4/] Corrosion	Source[3/]
Cu-Ni, 90-10	706	W	402	2370	0.6	U[5/]	NCEL
Cu-Ni, 90-10	706	W	402	2370	0.8	U	INCO[9/]
Cu-Ni, 90-10	706	S	402	2370	0.5	U[5/]	NCEL
Cu-Ni, 90-10	706	S	402	2370	0.1	ET	INCO[9/]
Cu-Ni, 90-10	706	W	181	5	1.1	NU	NCEL
Cu-Ni, 90-10	706	W	181	5	0.9	U	INCO[9/]
Cu-Ni, 90-10[6/]	-	W	402	2370	0.7	U	INCO[9/]
Cu-Ni, 90-10[6/]	-	S	402	2370	0.1	ET	INCO[9/]
Cu-Ni, 90-10[6/]	-	W	181	5	1.1	U	INCO[9/]
Cu-Ni, 80-20	710	W	123	5640	1.2	U	NCEL
Cu-Ni, 80-20	-	W	123	5640	1.9	U	INCO[9/]
Cu-Ni, 80-20	710	S	123	5640	1.3	U	NCEL
Cu-Ni, 80-20	-	S	123	5640	1.1	U	INCO[9/]
Cu-Ni, 80-20	710	W	403	6780	1.2	ET	NCEL
Cu-Ni, 80-20	-	W	403	6780	1.5	U	INCO[9/]
Cu-Ni, 80-20	710	S	403	6780	1.0	ET	NCEL
Cu-Ni, 80-20	-	S	403	6780	0.1	EBSL	INCO[9/]
Cu-Ni, 80-20	710	W	751	5640	0.8	U	NCEL
Cu-Ni, 80-20	-	W	751	5640	1.3	U	INCO[9/]
Cu-Ni, 80-20	-	S	751	5640	1.0	U	INCO[9/]
Cu-Ni, 80-20	-	W	1064	5300	1.0	U	INCO[9/]
Cu-Ni, 80-20	-	S	1064	5300	0.5	U	INCO[9/]
Cu-Ni, 80-20	710	W	197	2340	0.7	U	NCEL
Cu-Ni, 80-20	-	W	197	2340	1.1	U	INCO[9/]
Cu-Ni, 80-20	710	S	197	2340	0.5	U	NCEL
Cu-Ni, 80-20	-	S	197	2340	<0.1	SL ET	INCO[9/]
Cu-Ni, 80-20	710	W	402	2370	0.6	U	NCEL

Table 15. Corrosion Rates and Types of Corrosion of Copper-Nickel Alloys (cont'd)

Alloy	CDA No.[1]	Environment[2]	Exposure, Days	Depth, Feet	Corrosion Rate, MPY	Type of[4] Corrosion	Source[3]
Cu-Ni, 80-20	-	W	402	2370	1.1	U	INCO[9]
Cu-Ni, 80-20	710	S	402	2370	0.5	U[7]	NCEL
Cu-Ni, 80-20	-	S	402	2370	0.2	ET	INCO[9]
Cu-Ni, 80-20	-	W	181	5	2.8	G	INCO[9]
Cu-Ni, 70-30, 0.5 Fe	715	W	123	5640	1.2	U	NCEL
Cu-Ni, 70-30, 0.5 Fe	715	W	123	5640	1.3	U	INCO[9]
Cu-Ni, 70-30, 0.5 Fe	715	S	123	5640	0.8	U	NCEL
Cu-Ni, 70-30, 0.5 Fe	715	S	123	5640	0.9	U	INCO[9]
Cu-Ni, 70-30, 0.5 Fe	715	W	403	6780	1.2	U	NCEL
Cu-Ni, 70-30, 0.5 Fe	715	W	403	6780	1.2	U	INCO[9]
Cu-Ni, 70-30, 0.5 Fe	715	S	403	6780	1.1	U	NCEL
Cu-Ni, 70-30, 0.5 Fe	715	S	403	6780	0.2	G	INCO[9]
Cu-Ni, 70-30, 0.5 Fe	715	W	751	5640	0.7	U	NCEL
Cu-Ni, 70-30, 0.5 Fe	715	W	751	5640	0.9	G	INCO[9]
Cu-Ni, 70-30, 0.5 Fe	715	S	751	5640	0.7	U	INCO[9]
Cu-Ni, 70-30, 0.5 Fe	715	W	1064	5300	0.6	U	INCO[9]
Cu-Ni, 70-30, 0.5 Fe	715	S	1064	5300	0.5	G	INCO[9]
Cu-Ni, 70-30, 0.5 Fe	715	W	123	2500	0.6	U	NCEL
Cu-Ni, 70-30, 0.5 Fe	715	W	197	2340	0.7	U	NCEL
Cu-Ni, 70-30, 0.5 Fe	715	W	197	2340	0.9	U	INCO[9]
Cu-Ni, 70-30, 0.5 Fe	715	S	197	2340	0.2	U	NCEL
Cu-Ni, 70-30, 0.5 Fe	715	S	197	2340	<0.1	SL ET	INCO[9]
Cu-Ni, 70-30, 0.5 Fe	715	W	402	2370	0.5	U	NCEL
Cu-Ni, 70-30, 0.5 Fe	715	W	402	2370	0.6	U	INCO[9]
Cu-Ni, 70-30, 0.5 Fe	715	S	402	2370	0.4	U	NCEL
Cu-Ni, 70-30, 0.5 Fe	715	S	402	2370	0.1	ET	INCO[9]

Table 15. Corrosion Rates and Types of Corrosion of Copper-Nickel Alloys (cont'd)

Alloy	CDA No.[1]	Environ-ment[2]	Exposure, Days	Depth, Feet	Corrosion Rate, MPY	Type of[4] Corrosion	Source[3]
Cu-Ni, 70-30, 0.5 Fe	715	W	181	5	0.5	U	NCEL
Cu-Ni, 70-30, 0.5 Fe	715	W	181	5	0.5	G	INCO[9]
Cu-Ni, 70-30, 5 Fe	-	W	123	5640	0.2	U	NCEL
Cu-Ni, 70-30, 5 Fe	-	S	123	5640	0.2	U	NCEL
Cu-Ni, 70-30, 5 Fe	-	W	403	6780	0.1	ET	NCEL
Cu-Ni, 70-30, 5 Fe	-	S	403	6780	0.1	ET	NCEL
Cu-Ni, 70-30, 5 Fe	-	W	751	5640	0.5	C, 16; NU P 16m, 8.5a; CO	NCEL
Cu-Ni, 70-30, 5 Fe	-	S	751	5640	0.2	C, 14; NU P 24m, 8a; CO	NCEL
Cu-Ni, 70-30, 5 Fe	-	W	197	2340	0.1	U	NCEL
Cu-Ni, 70-30, 5 Fe	-	S	197	2340	0.1	U	NCEL
Cu-Ni, 70-30, 5 Fe	-	W	402	2370	0.1	U	NCEL
Cu-Ni, 70-30, 5 Fe	-	S	402	2370	0.1	U	NCEL
Cu-Ni, 70-30, 5 Fe	-	W	181	5	0.8	IP; C, 5	NCEL
Cu-Ni, 55-45	-	W	123	5640	0.7	U	INCO[9]
Cu-Ni, 55-45	-	S	123	5640	0.7	U	INCO[9]
Cu-Ni, 55-45	-	W	403	6780	1.2	U	INCO[9]
Cu-Ni, 55-45	-	S	403	6780	<0.1	SL ET	INCO[9]
Cu-Ni, 55-45	-	W	751	5640	1.0	U	INCO[9]
Cu-Ni, 55-45	-	S	751	5640	0.5	U	INCO[9]
Cu-Ni, 55-45	-	W	1064	5300	1.0	G	INCO[9]
Cu-Ni, 55-45	-	S	1064	5300	0.5	C to PR, 50; S E	INCO[9]
Cu-Ni, 55-45	-	W	197	2340	0.8	U	INCO[9]
Cu-Ni, 55-45	-	S	197	2340	0.2	IC, IP	INCO[9]

Table 15. Corrosion Rates and Types of Corrosion of Copper-Nickel Alloys (cont'd)

Alloy	CDA No.[1]	Environment[2]	Exposure, Days	Depth, Feet	Corrosion Rate, MPY	Type of[4] Corrosion	Source[3]
Cu-Ni, 55-45	-	W	402	2370	0.7	U	INCO[9]
Cu-Ni, 55-45	-	S	402	2370	0.1	ET	INCO[9]
Cu-Ni, 55-45	-	W	181	5	1.8	U	INCO[9]
Cu-Ni-Zn-Pb	-	W	123	5640	0.9	U	INCO[9]
Cu-Ni-Zn-Pb	-	S	123	5640	0.6	U	INCO[9]
Cu-Ni-Zn-Pb	-	W	403	6780	0.8	U	INCO[9]
Cu-Ni-Zn-Pb	-	S	403	6780	0.1	GBSL	INCO[9]
Cu-Ni-Zn-Pb	-	W	751	5640	0.6	U	INCO[9]
Cu-Ni-Zn-Pb	-	S	751	5640	0.5	U	INCO[9]
Cu-Ni-Zn-Pb	-	W	1064	5300	0.5	U	INCO[9]
Cu-Ni-Zn-Pb	-	S	1064	5300	0.3	U	INCO[9]
Cu-Ni-Zn-Pb	-	W	197	2340	0.5	U	INCO[9]
Cu-Ni-Zn-Pb	-	S	197	2340	<0.1	SL ET	INCO[9]
Cu-Ni-Zn-Pb	-	W	402	2370	0.4	U	INCO[9]
Cu-Ni-Zn-Pb	-	S	402	2370	<0.1	ET	INCO[9]
Cu-Ni-Zn-Pb	-	W	181	5	1.0	U	INCO[9]
Nickel-Silver	752	W	123	5640	2.0	U	INCO[9]
Nickel-Silver	752	S	123	5640	2.6	U	INCO[9]
Nickel-Silver	752	W	403	6780	1.4	U	INCO[9]
Nickel-Silver	752	S	403	6780	0.5	GBSL	INCO[9]
Nickel-Silver	752	W	751	5640	1.5	U	INCO[9]
Nickel-Silver	752	S	751	5640	0.8	U	INCO[9]
Nickel-Silver	752	W	1064	5300	0.6	U	INCO[9]
Nickel-Silver	752	S	1064	5300	0.4	G	INCO[9]
Nickel-Silver	752	W	197	2340	1.0	U	INCO[9]
Nickel-Silver	752	S	197	2340	<0.1	SL ET	INCO[9]

Table 15. Corrosion Rates and Types of Corrosion of Copper-Nickel Alloys (cont'd)

Alloy	CDA No.[1]	Environment[2]	Exposure, Days	Depth, Feet	Corrosion Rate, MPY	Type of[4] Corrosion	Source[3]
Nickel-Silver	752	W	402	2370	1.0	U	INCO[9]
Nickel-Silver	752	S	402	2370	0.1	ET	INCO[9]
Nickel-Silver	752	W	181	5	1.1	U	INCO[9]

[1] Copper Development Association alloy numbers

[2] W - Totally exposed in sea water on sides of structure
S - Exposed in base of structure so that a portion of each specimen was embedded in the bottom sediments.

[3] Numbers refer to references at end of paper

[4] Symbols for types of corrosion

C - Crevice
E - Edge
ET - Etching
EBSL - Etched below sediment line
G - General
GBSL - General below sediment line
I - Incipient
NU - Non-Uniform
P - Pitting
S - Severe
SL - Slight
U - Uniform

Table 15. Corrosion Rates and Types of Corrosion of Copper-Nickel Alloys (cont'd)

4/ Symbols for types of corrosion (cont'd)

Numbers refer to mils
i.e. 20 - 20 mils
20m - 20 mils maximum
14.6a - 14.6 mils average

5/ Much less below sediment line

6/ Cast alloy

7/ No visible corrosion below sediment line

Table 16. Stress Corrosion of Copper-Nickel Alloys

Alloy	CDA No.[1/]	Stress, KSI	Tensile Strength, o/o	Exposure		Specimens	
				Days	Depth, Feet	Exposed	Failed
Cu-Ni, 95-5	704	16.0	50	403	6780	2	0
Cu-Ni, 95-5	704	24.0	75	403	6780	2	0
Cu-Ni, 95-5	704	16.0	50	197	2340	3	0
Cu-Ni, 95-5	704	24.0	75	197	2340	3	0
Cu-Ni, 95-5	704	12.9	50	402	2370	3	0
Cu-Ni, 95-5	704	19.3	75	402	2370	3	0
Cu-Ni, 90-10	706	34.4	50	402	2370	3	0
Cu-Ni, 90-10	706	52.0	75	402	2370	3	0
Cu-Ni, 80-20	710	15.0	75	403	6780	2	0
Cu-Ni, 80-20	710	15.0	75	197	2340	3	0
Cu-Ni, 80-20	710	8.9	50	402	2370	3	0
Cu-Ni, 80-20	710	13.3	75	402	2370	3	0
Cu-Ni, 70-30, 0.5 Fe	715	13.0	50	403	6780	2	0
Cu-Ni, 70-30, 0.5 Fe	715	20.0	75	403	6780	2	0
Cu-Ni, 70-30, 0.5 Fe	715	13.2	50	197	2340	3	0
Cu-Ni, 70-30, 0.5 Fe	715	19.8	75	197	2340	3	0
Cu-Ni, 70-30, 0.5 Fe	715	14.0	50	402	2370	3	0
Cu-Ni, 70-30, 0.5 Fe	715	21.0	75	402	2370	3	0
Cu-Ni, 70-30, 5.0 Fe	-	14.0	35	403	6780	2	0
Cu-Ni, 70-30, 5.0 Fe	-	21.0	50	403	6780	2	0
Cu-Ni, 70-30, 5.0 Fe	-	31.0	75	403	6780	2	0
Cu-Ni, 70-30, 5.0 Fe	-	14.4	35	197	2340	3	0
Cu-Ni, 70-30, 5.0 Fe	-	20.6	50	197	2340	3	0
Cu-Ni, 70-30, 5.0 Fe	-	30.9	75	197	2340	3	0
Cu-Ni, 70-30, 5.0 Fe	-	26.6	50	402	2370	3	0
Cu-Ni, 70-30, 5.0 Fe	-	39.9	75	402	2370	3	0

[1/] Copper Development Association alloy number

Table 17. Changes in Mechanical Properties of Copper-Nickel Alloys Due to Corrosion

Alloy	CDA No.[1]	Exposure		Original Properties			Percent Change		
		Days	Depth, Feet	Tensile Strength, KSI	Yield Strength, KSI	Elongation Percent	Tensile Strength	Yield Strength	Elongation
Cu-Ni, 95-5	704	-	-	47.6	32.0	33.3	-	-	-
Cu-Ni, 95-5	704	123	5640	-	-	-	+1.1	+16.3	+2.1
Cu-Ni, 95-5	704	403	6780	-	-	-	+2.0	+3.3	-4.6
Cu-Ni, 95-5	704	751	5640	-	-	-	-0.8	-3.0	+2.0
Cu-Ni, 95-5	704	197	2340	-	-	-	-3.5	-8.9	+6.8
Cu-Ni, 95-5	704	402	2370	-	-	-	-0.6	-5.6	+4.0
Cu-Ni, 90-10	706	-	-	42.7	15.9	42.0	-	-	-
Cu-Ni, 90-10	706	123	5640	-	-	-	+3.3	+11.3	0.0
Cu-Ni, 90-10	706	403	6780	-	-	-	+3.4	+6.0	-4.9
Cu-Ni, 90-10	706	751	5640	-	-	-	+3.0	+8.8	-2.4
Cu-Ni, 90-10	706	197	2340	-	-	-	-0.7	+0.4	-2.4
Cu-Ni, 90-10	706	402	2370	-	-	-	+4.4	+12.6	-5.6
Cu-Ni, 80-20	710	-	-	49.1	20.5	43.6	-	-	-
Cu-Ni, 80-20	710	123	5640	-	-	-	-0.4	-2.9	+1.6
Cu-Ni, 80-20	710	403	6780	-	-	-	+2.3	-2.4	-2.9
Cu-Ni, 80-20	710	751	5640	-	-	-	+0.8	-1.9	-3.0
Cu-Ni, 80-20	710	197	2340	-	-	-	+0.7	-6.1	+1.1
Cu-Ni, 80-20	710	402	2370	-	-	-	+1.4	-1.5	-1.6
Cu-Ni, 70-30,0.5 Fe	715	-	-	58.3	26.4	41.2	-	-	-
Cu-Ni, 70-30,0.5 Fe	715	123	5640	-	-	-	+1.0	-2.3	+2.7
Cu-Ni, 70-30,0.5 Fe	715	403	6780	-	-	-	-25.0	-0.9	-3.3
Cu-Ni, 70-30,0.5 Fe	715	751	5640	-	-	-	-25.4	-4.2	-4.1

Table 17. Changes in Mechanical Properties of Copper-Nickel Alloys Due to Corrosion (cont'd)

Alloy	CDA No.[1/]	Exposure		Original Properties			Percent Change		
		Days	Depth, Feet	Tensile Strength, KSI	Yield Strength, KSI	Elongation Percent	Tensile Strength	Yield Strength	Elongation
Cu-Ni, 70-30,0.5 Fe	715	197	2340	-	-	-	-2.6	-14.3	+0.8
Cu-Ni, 70-30,0.5 Fe	715	402	2370	-	-	-	+2.3	-2.8	-3.2
Cu-Ni, 70-30,5.0 Fe	-	-	-	78.3	41.2	35.2	-	-	-
Cu-Ni, 70-30,5.0 Fe	-	123	5640	-	-	-	+2.2	+4.9	+0.9
Cu-Ni, 70-30,5.0 Fe	-	403	6780	-	-	-	-0.6	-3.3	-0.8
Cu-Ni, 70-30,5.0 Fe	-	751	5640	-	-	-	+3.4	+5.2	-9.4
Cu-Ni, 70-30,5.0 Fe	-	197	2340	-	-	-	+1.1	-4.0	0.0
Cu-Ni, 70-30,5.0 Fe	-	402	2370	-	-	-	+6.6	+9.6	-8.0

[1/] Copper Development Association alloy number

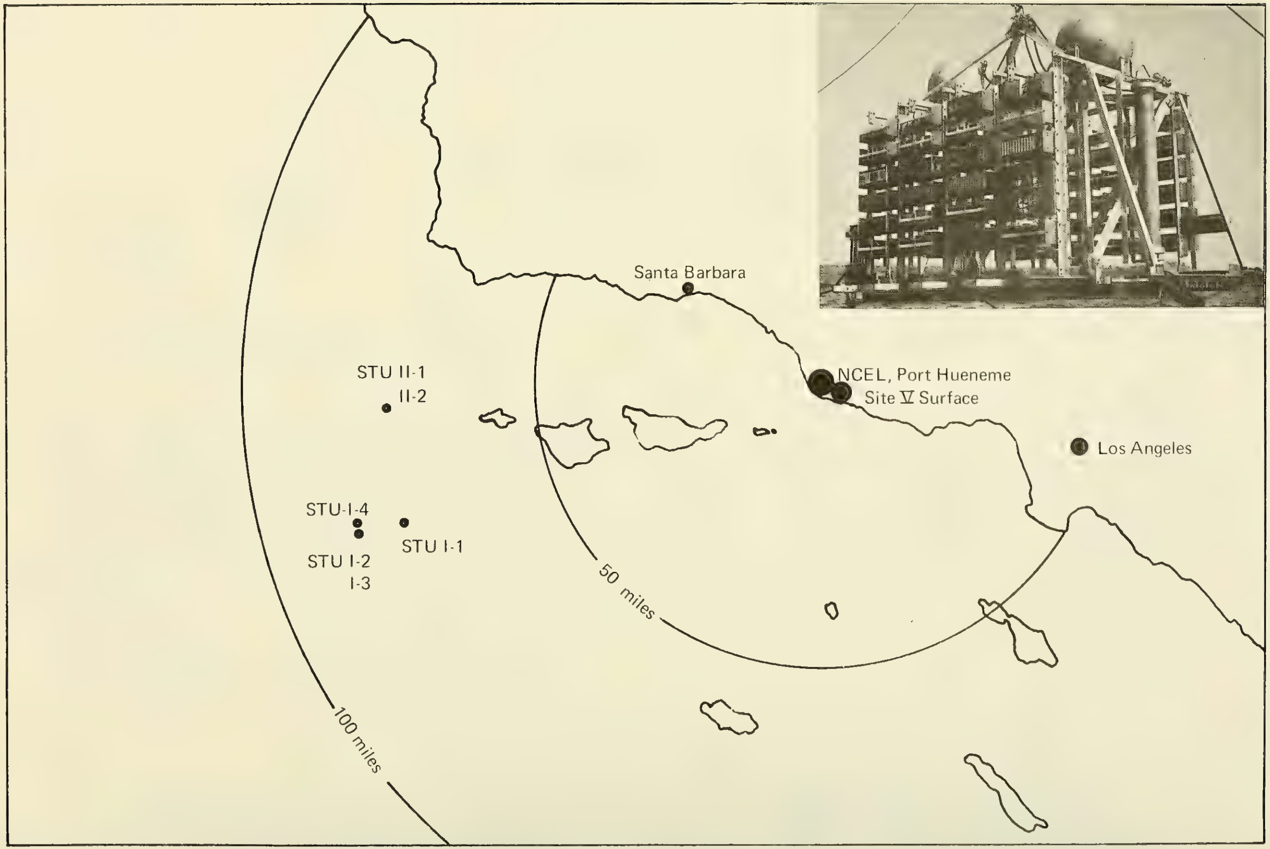

Figure 1. Area map showing STU sites off the Pacific Coast; STU structure in inset.

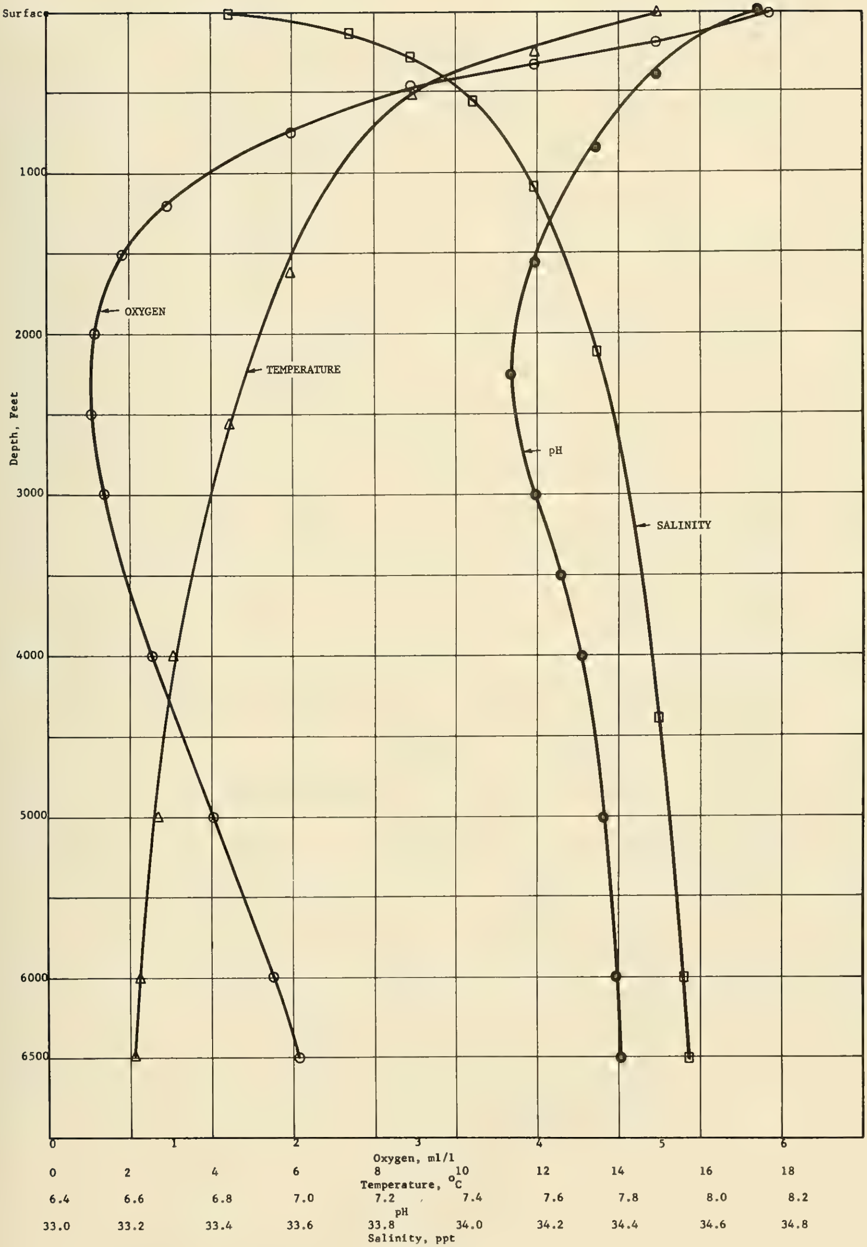

Figure 2. Oceanographic data at STU sites.

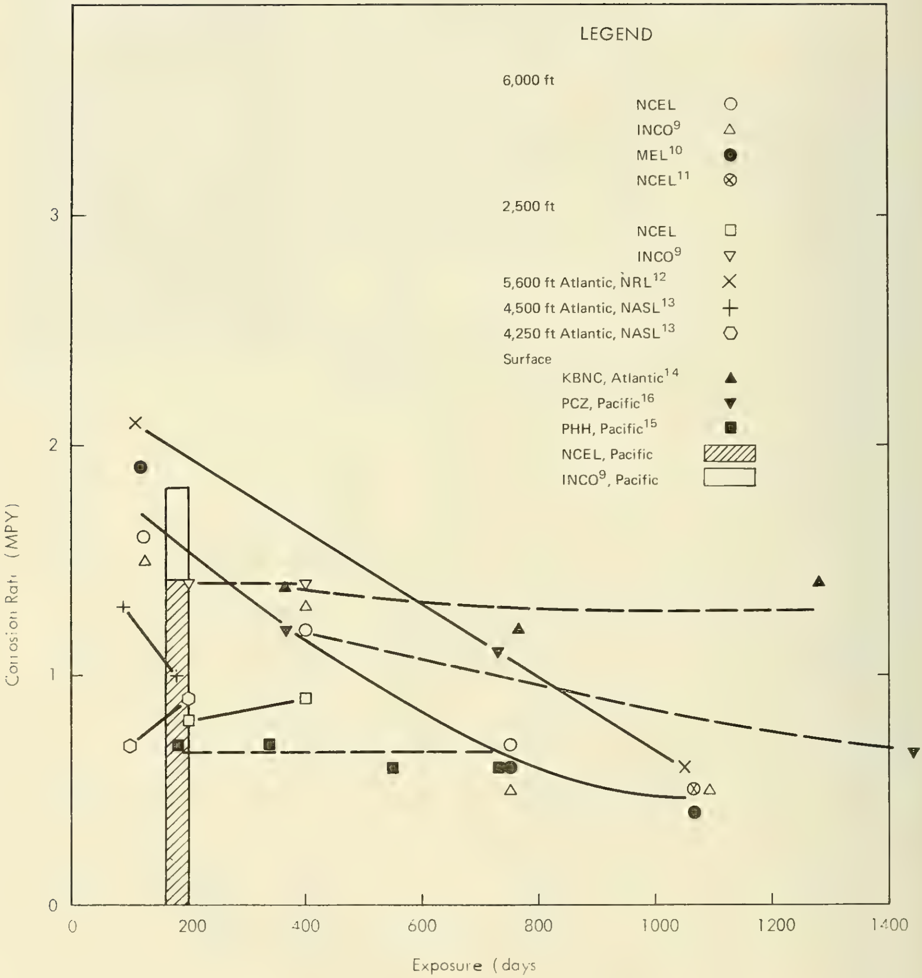

Figure 3. Corrosion rates of copper in sea water.

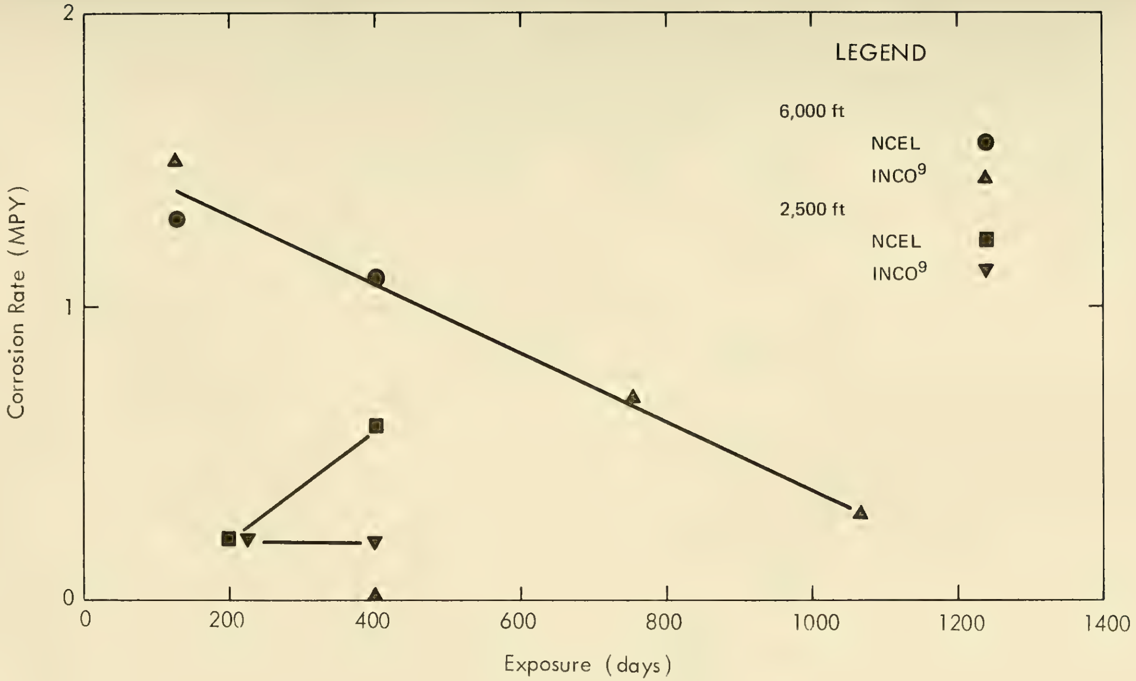

Figure 4. Corrosion rates of copper in bottom sediments.

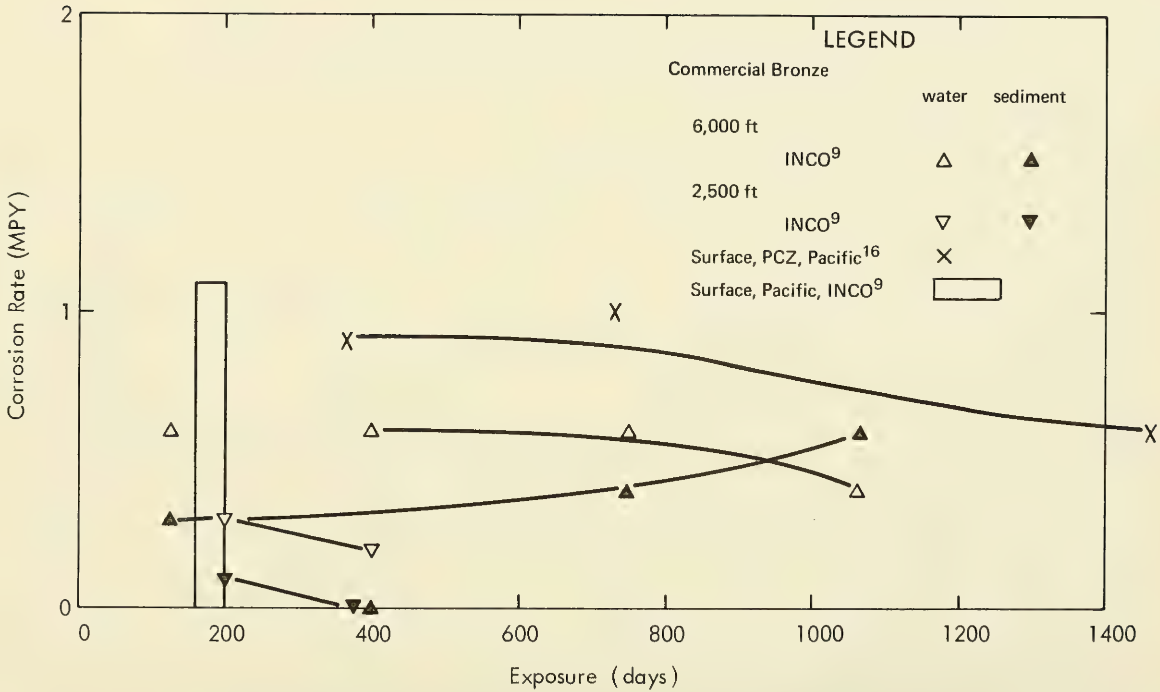

Figure 5. Corrosion rates of commercial bronze.

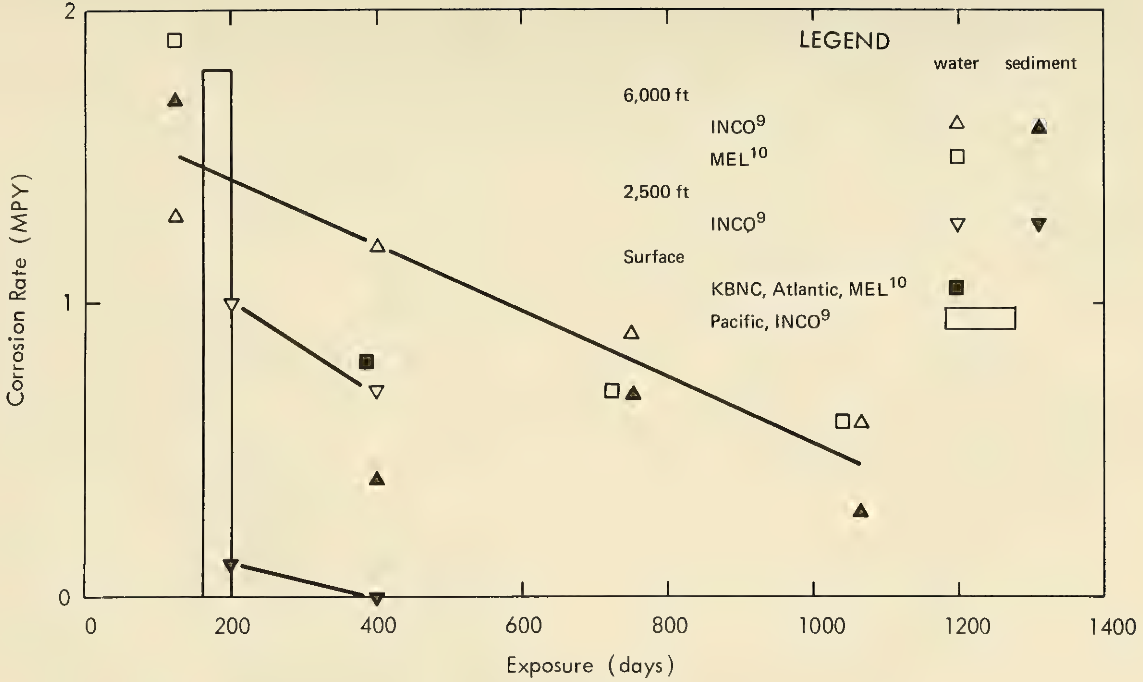

Figure 6. Corrosion rates of red brass.

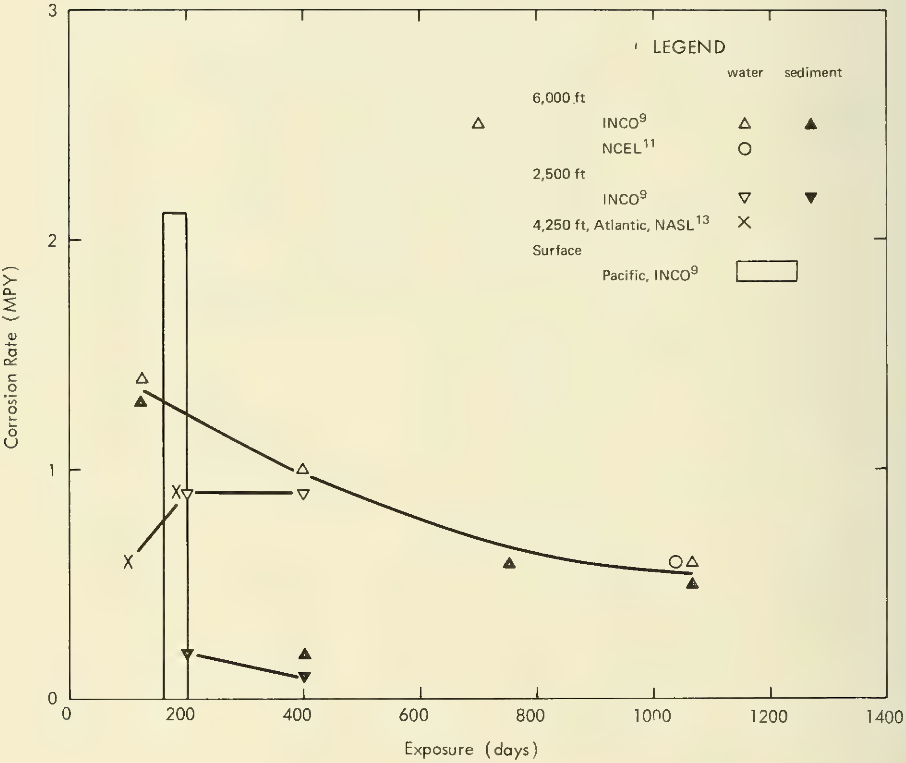

Figure 7. Corrosion rates of yellow brass.

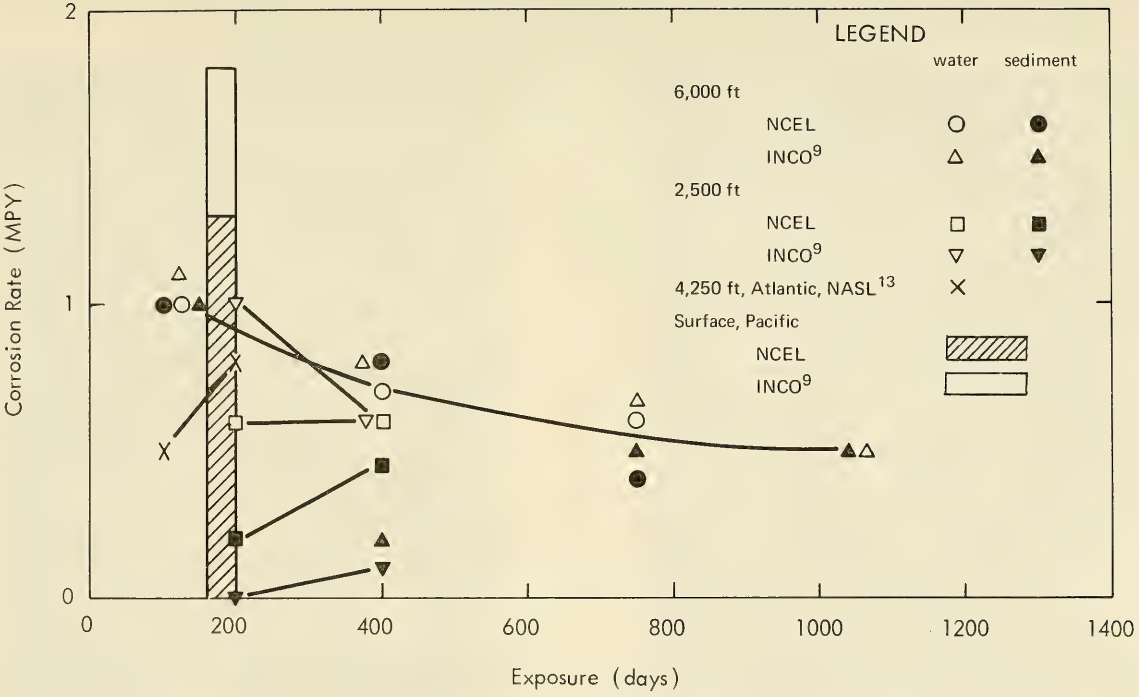

Figure 8. Corrosion rates of arsenical Admiralty brass.

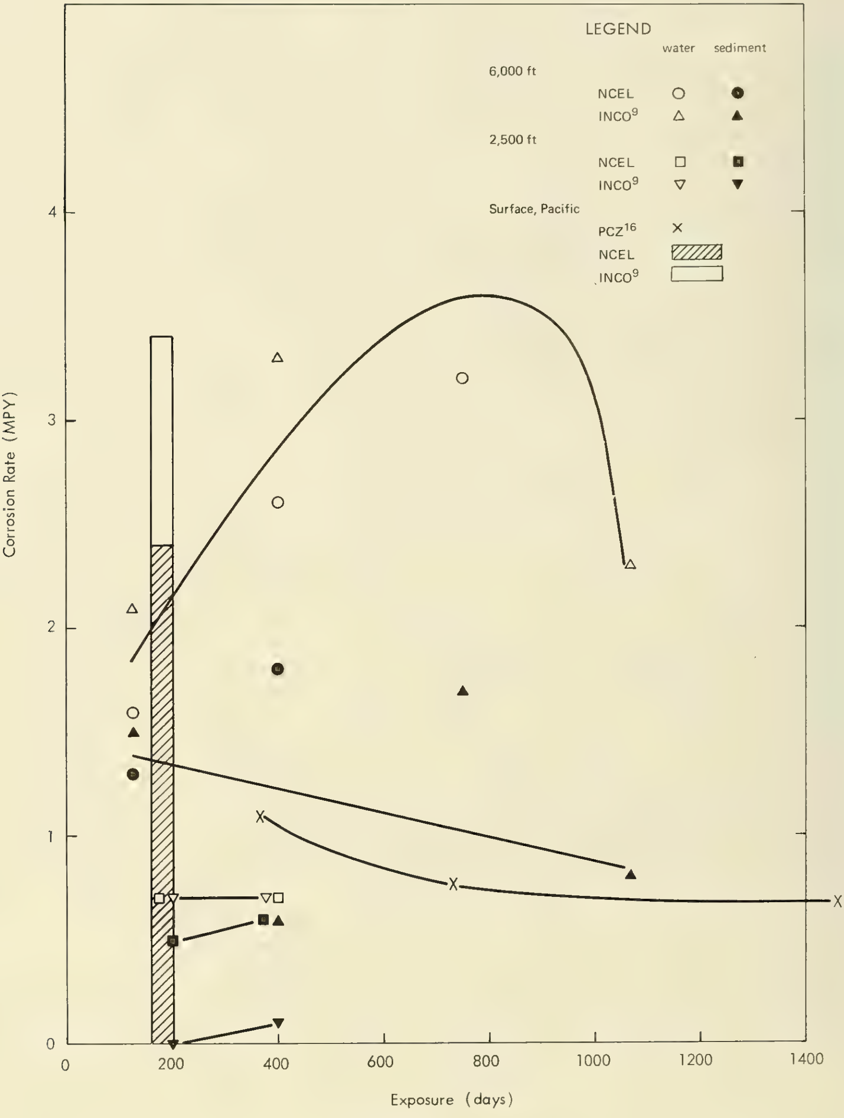

Figure 9. Corrosion rates of Muntz Metal.

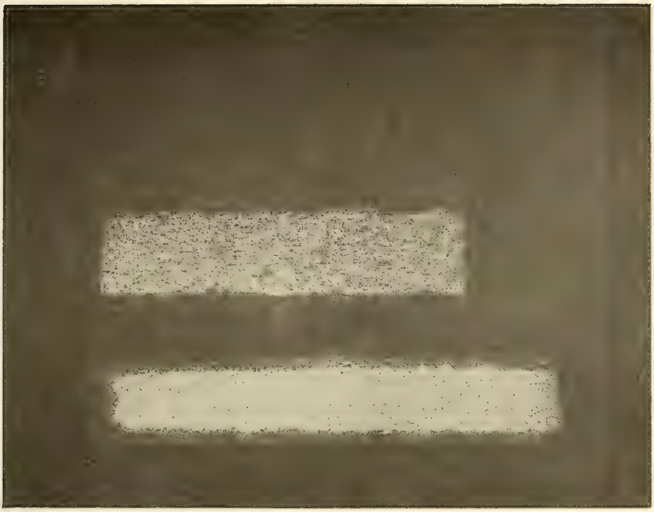

Figure 10. Dezincified Muntz metal, 751 days, 5640 feet. X3.

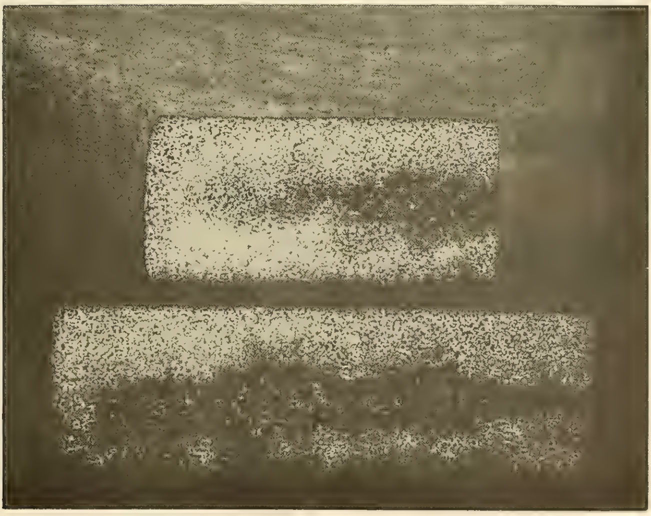

Figure 14. Dezincified nickel-manganese bronze, 751 days, 5640 feet. X3.

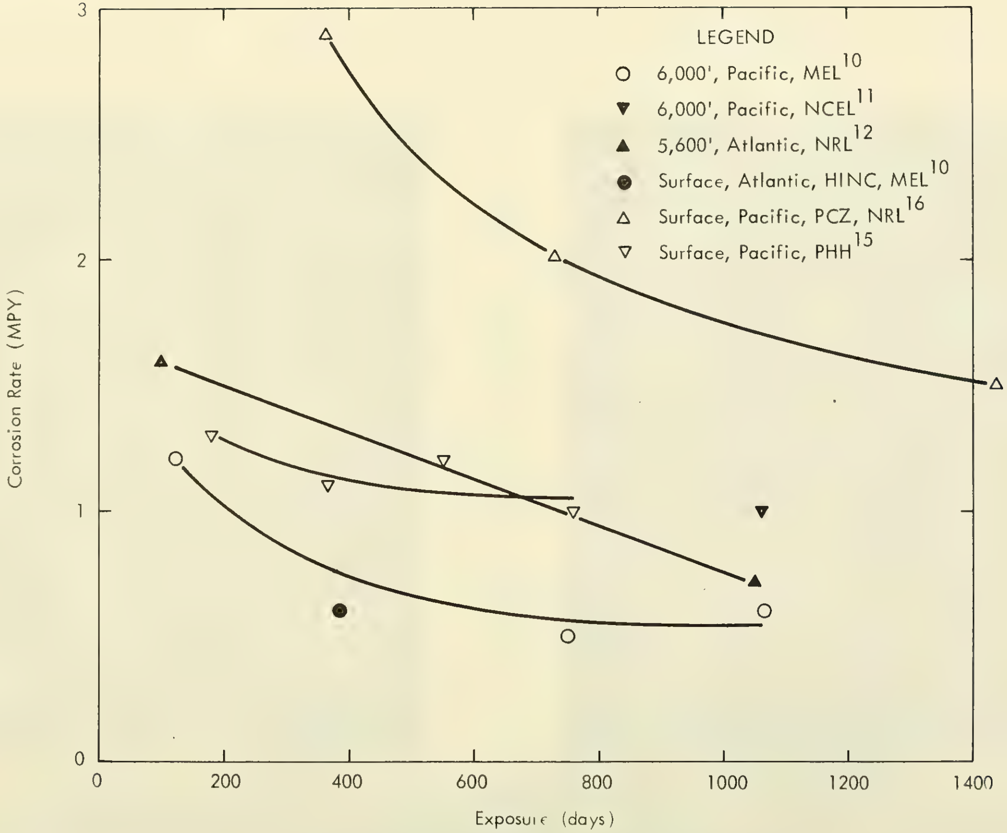

Figure 11. Corrosion rates of naval brass in sea water.

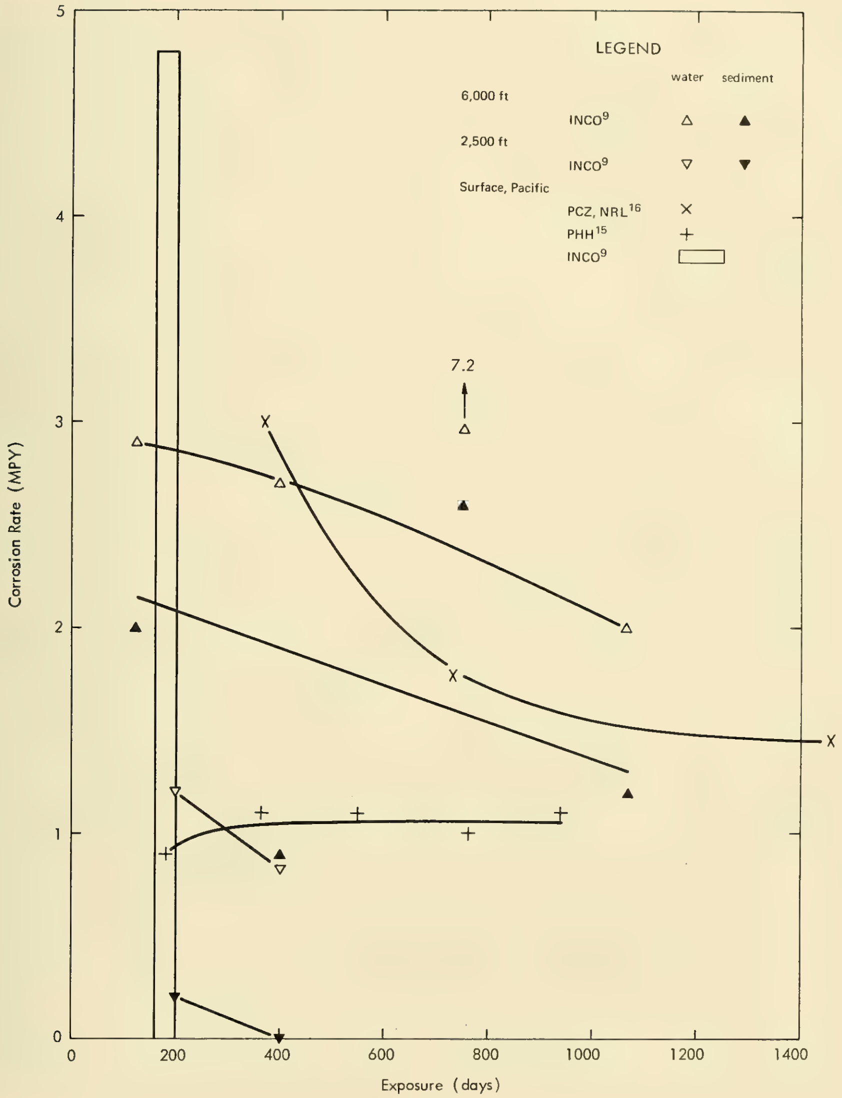

Figure 12. Corrosion rates of manganese bronze.

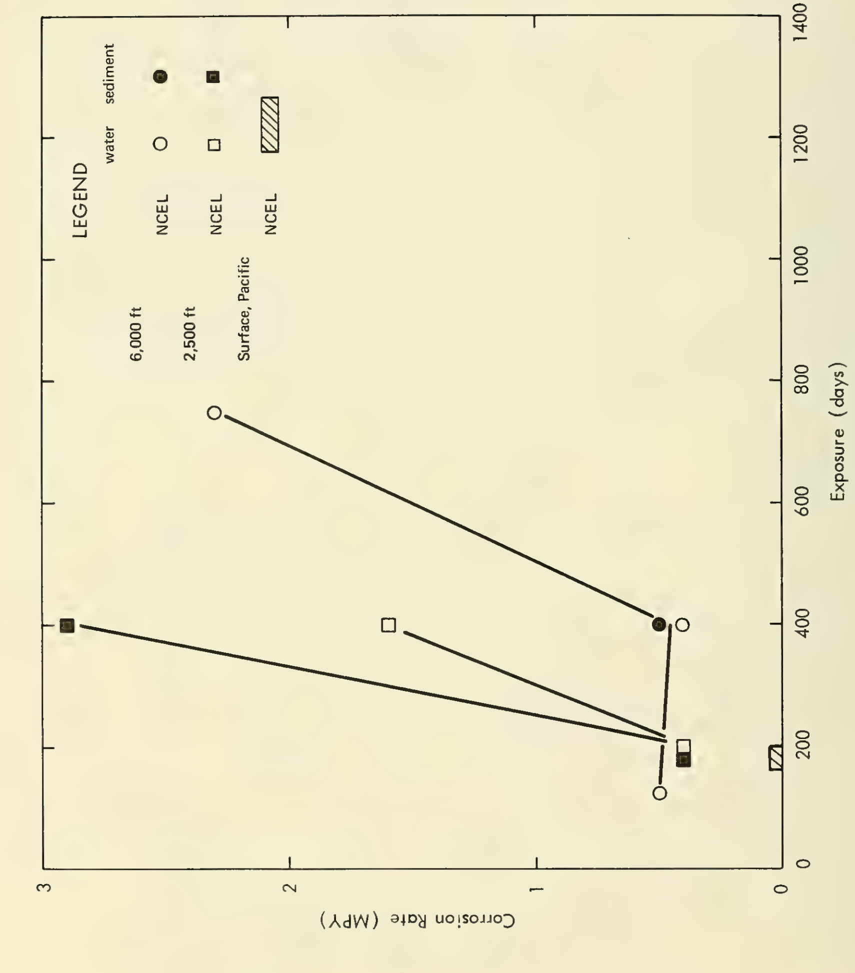

Figure 13. Corrosion rates of nickel - manganese bronze.

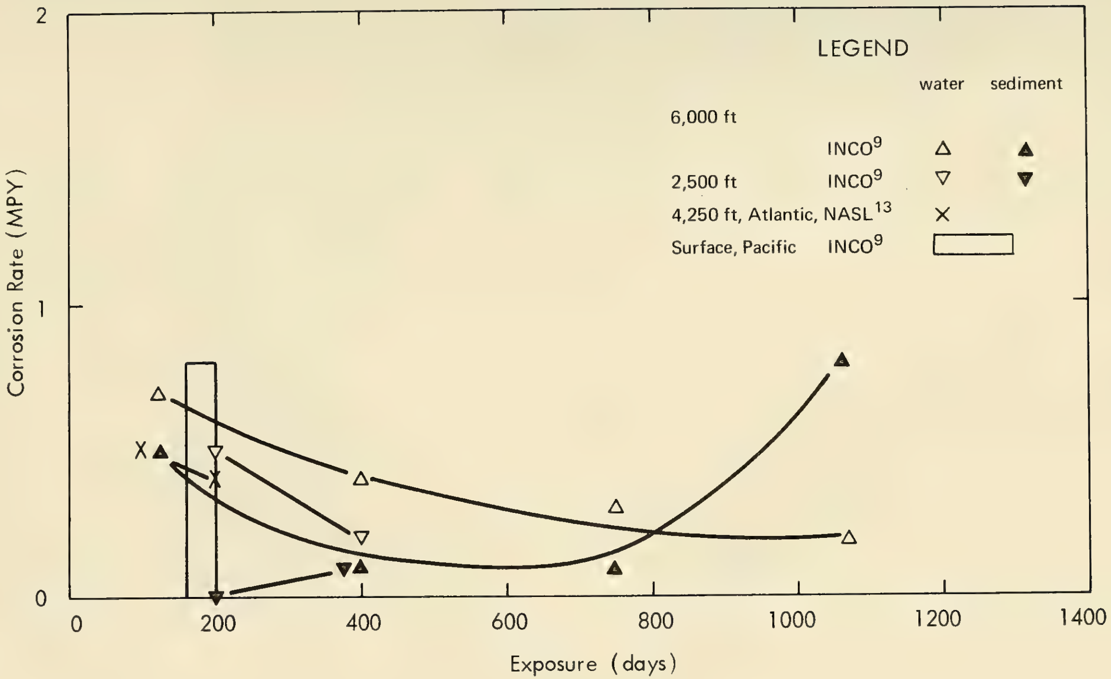

Figure 15. Corrosion rates of aluminum brass.

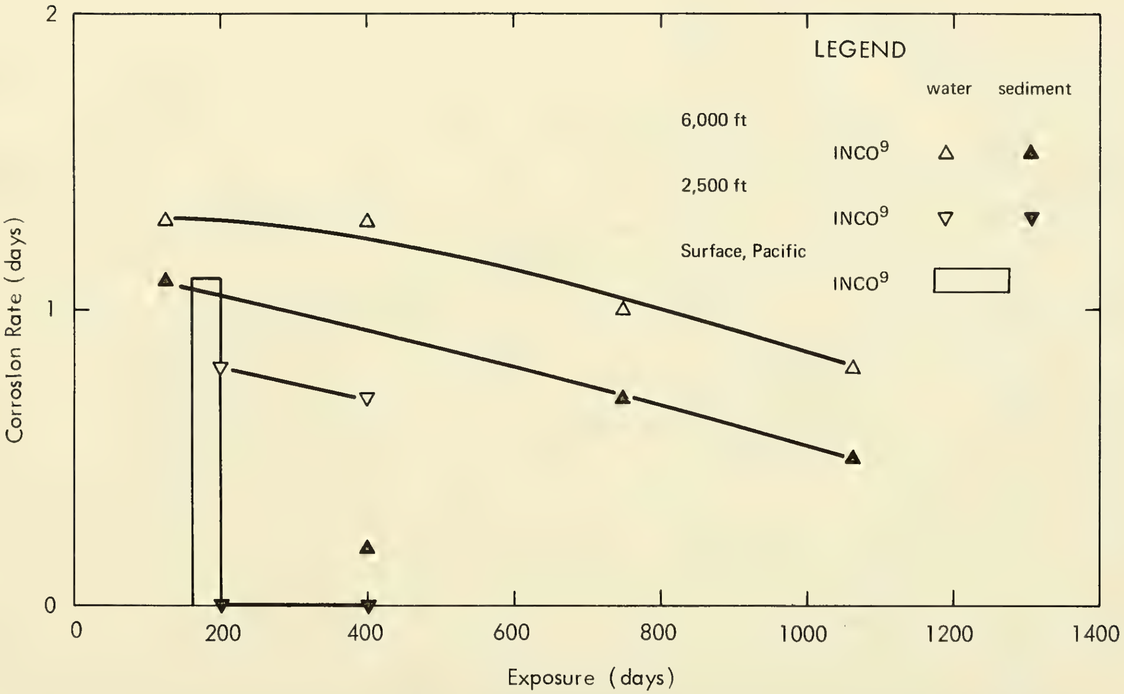

Figure 16. Corrosion rates of nickel-brass.

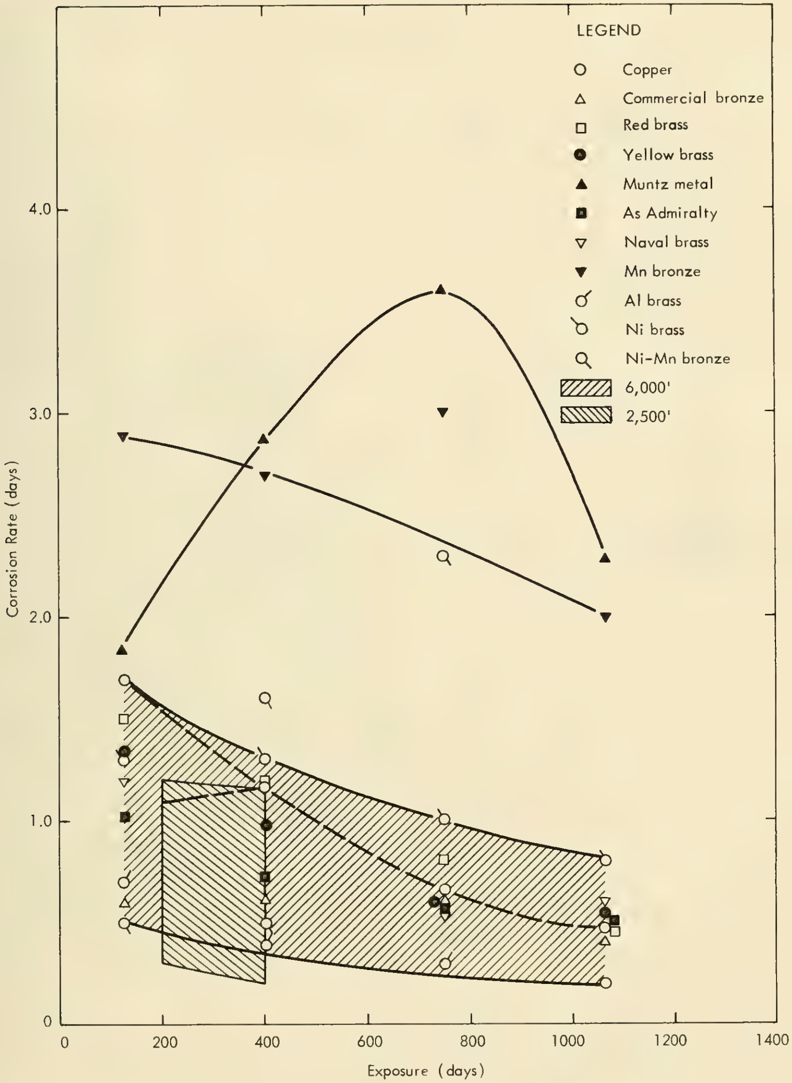

Figure 17. Corrosion rates of copper-zinc alloys in sea water.

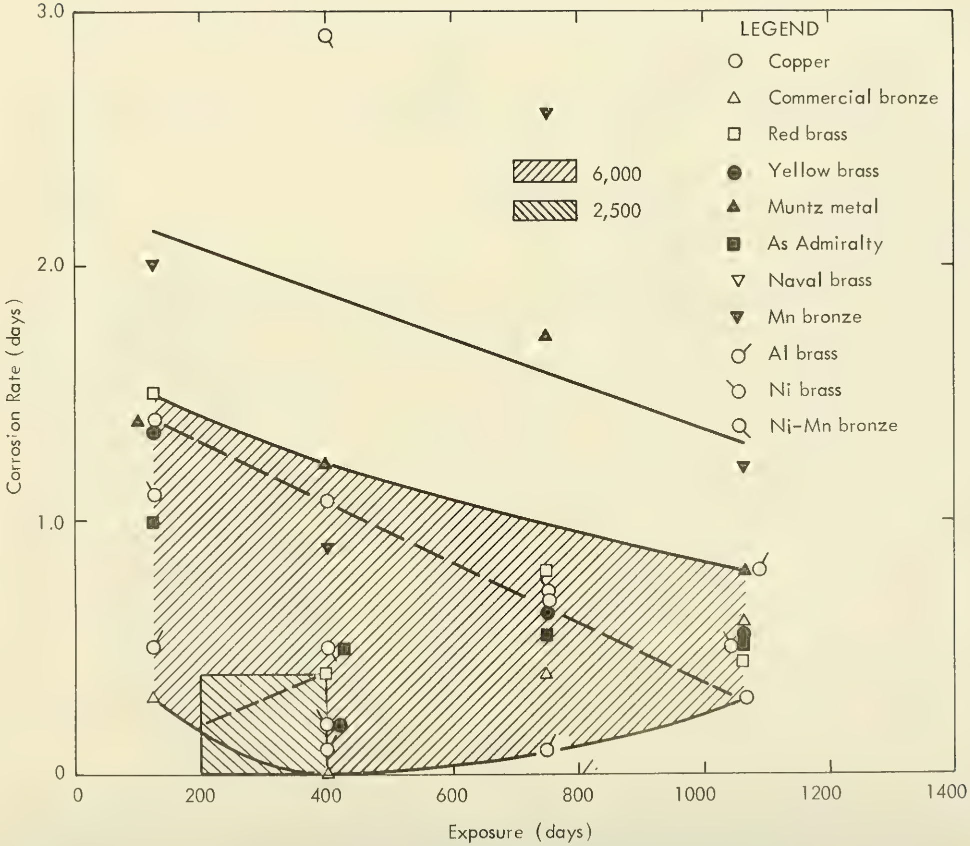

Figure 18. Corrosion rates of copper-zinc alloys in the bottom sediments.

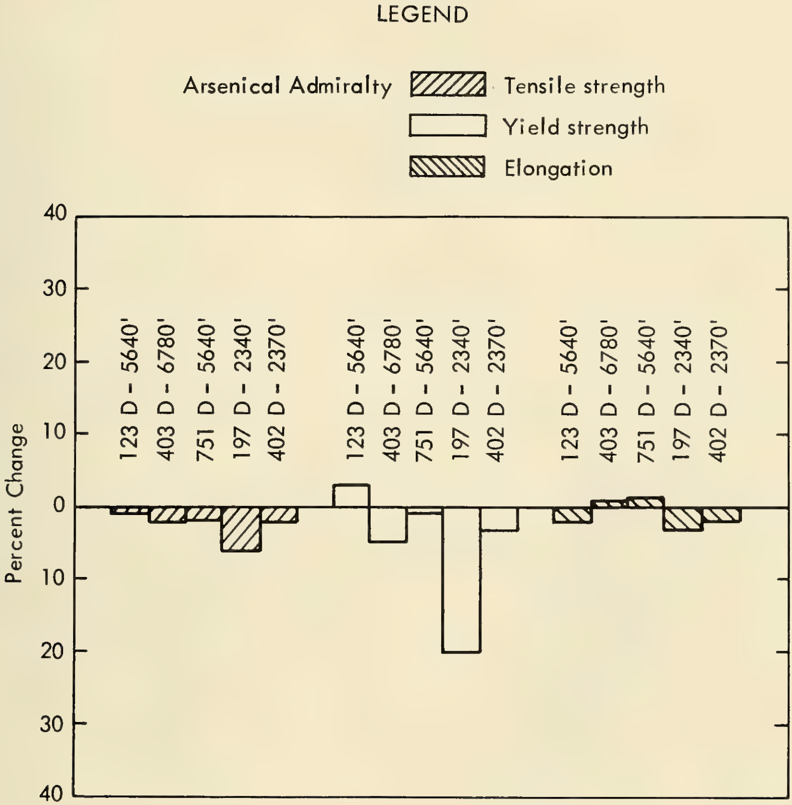

Figure 19. Effect of exposure on mechanical properties of arsenical Admiralty metal.

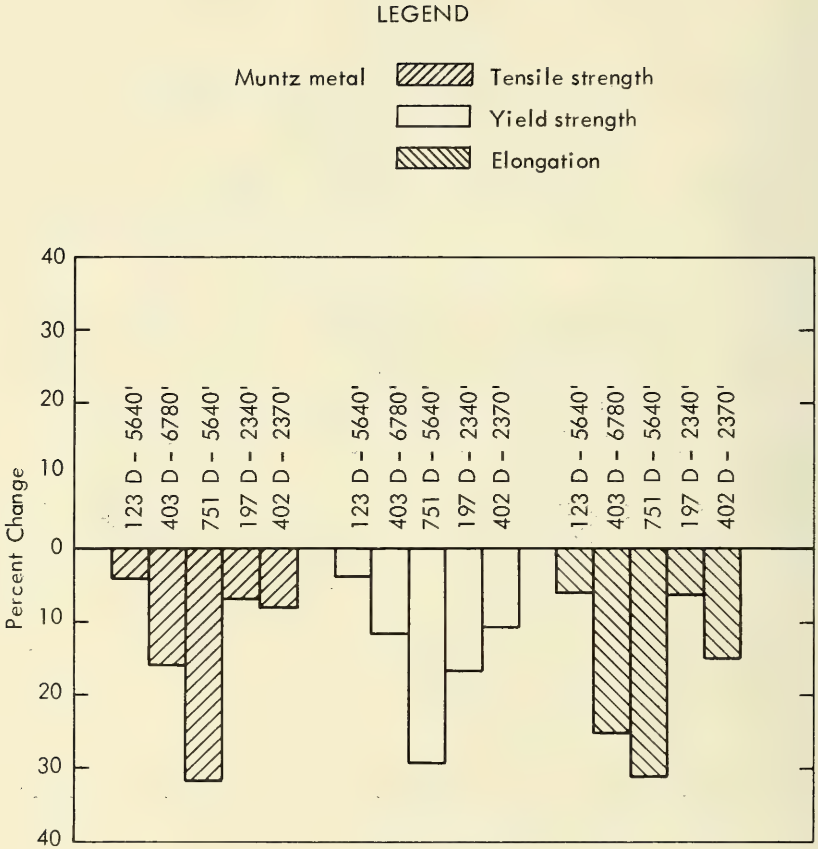

Figure 20. Effect of exposure on mechanical properties of Muntz metal.

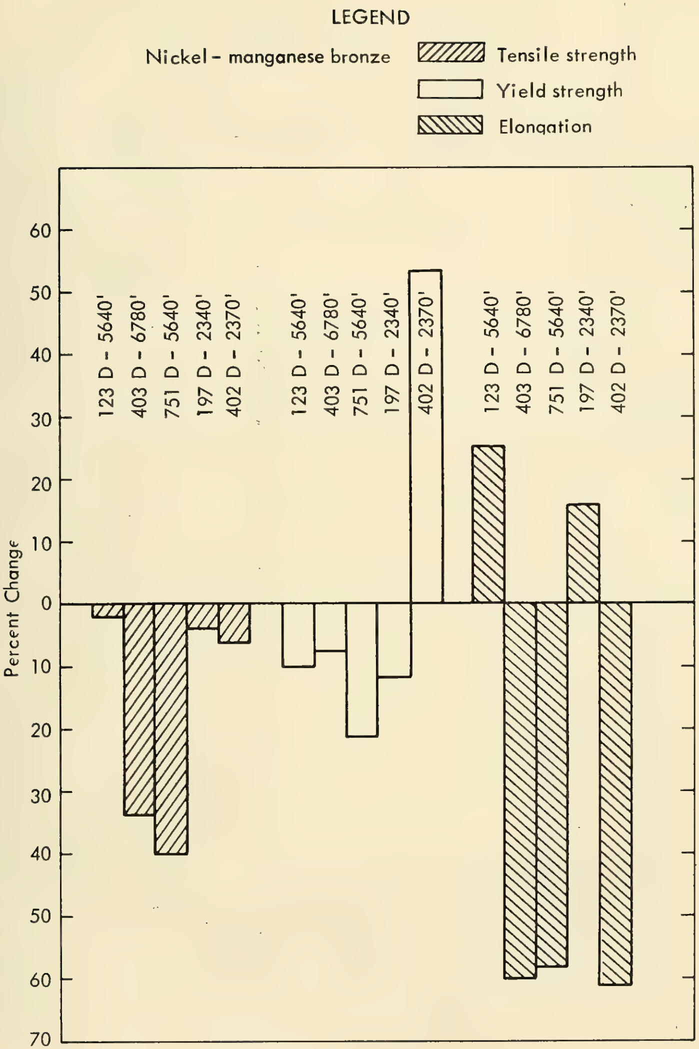

Figure 21. Effects of exposure on mechanical properties of nickel-manganese bronze.

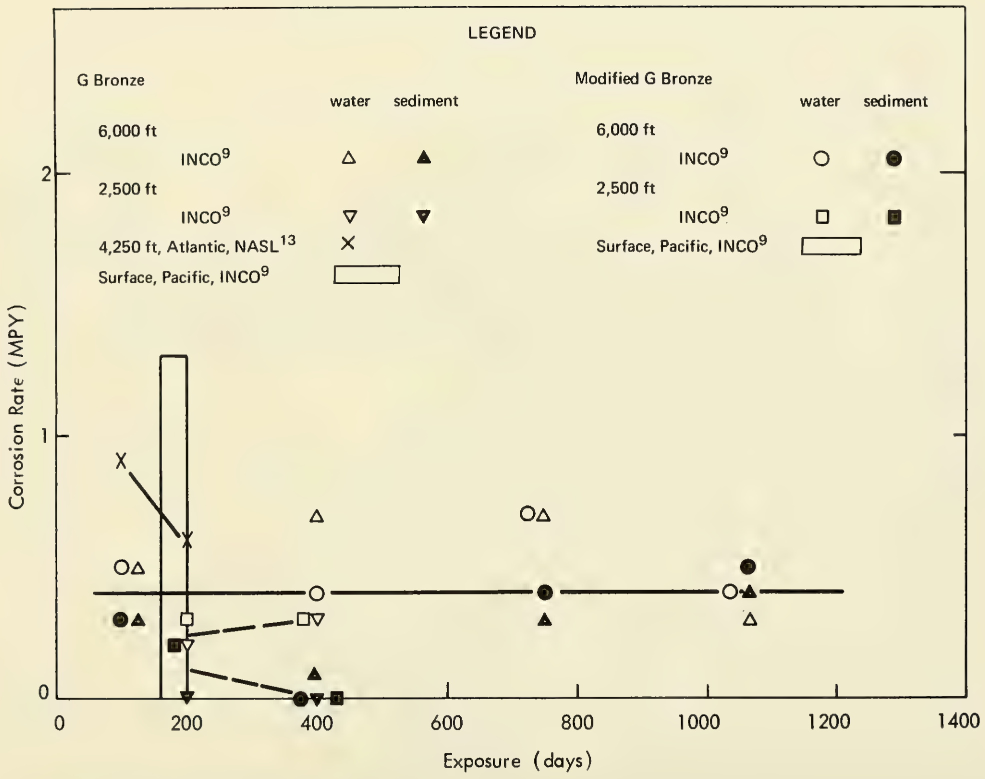

Figure 22. Corrosion rates of G and modified G Bronzes.

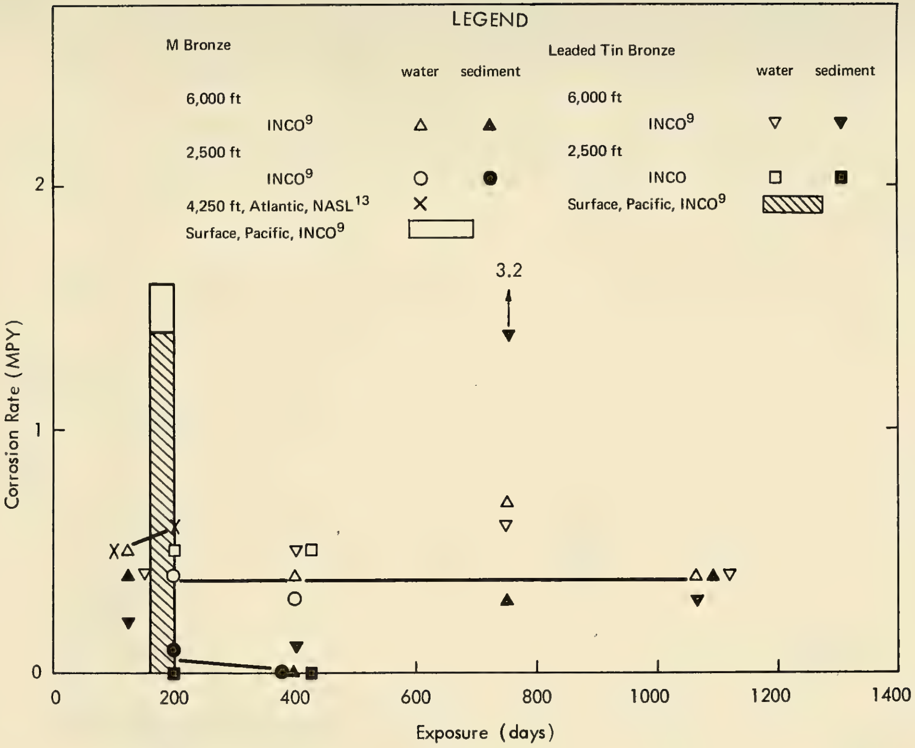

Figure 23. Corrosion rates of M Bronze and leaded tin Bronze

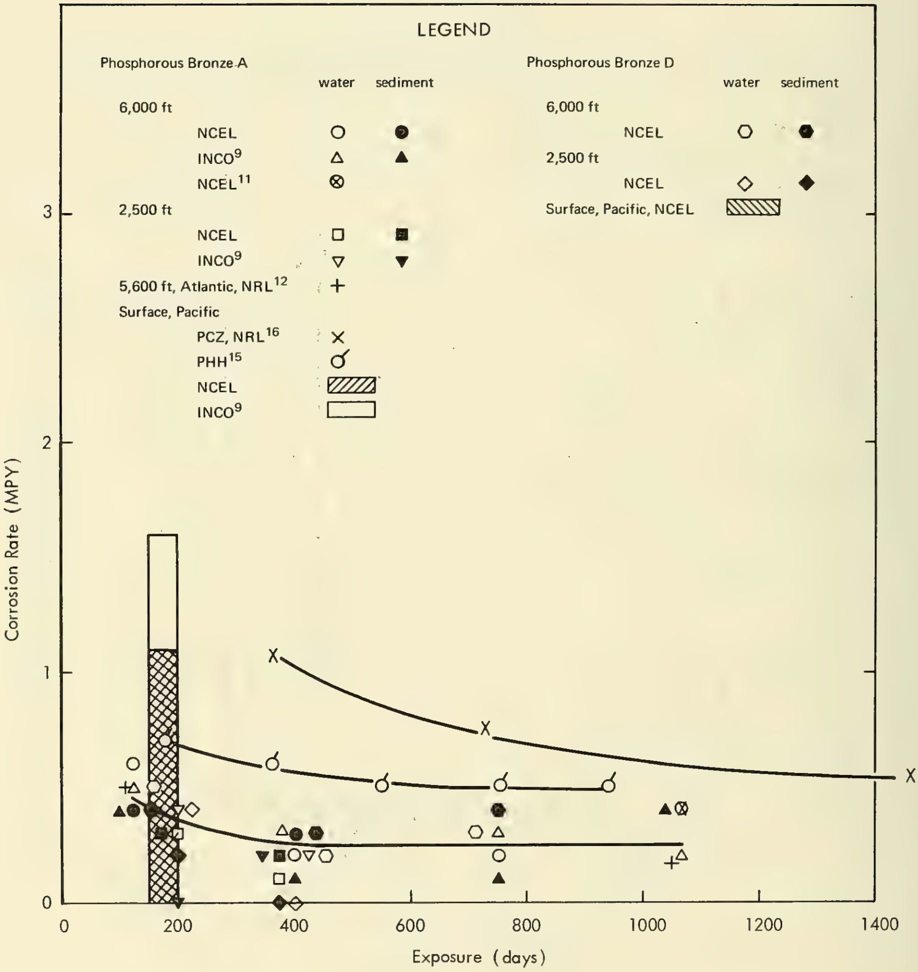

Figure 24. Corrosion rates of phosphorous bronzes A and D.

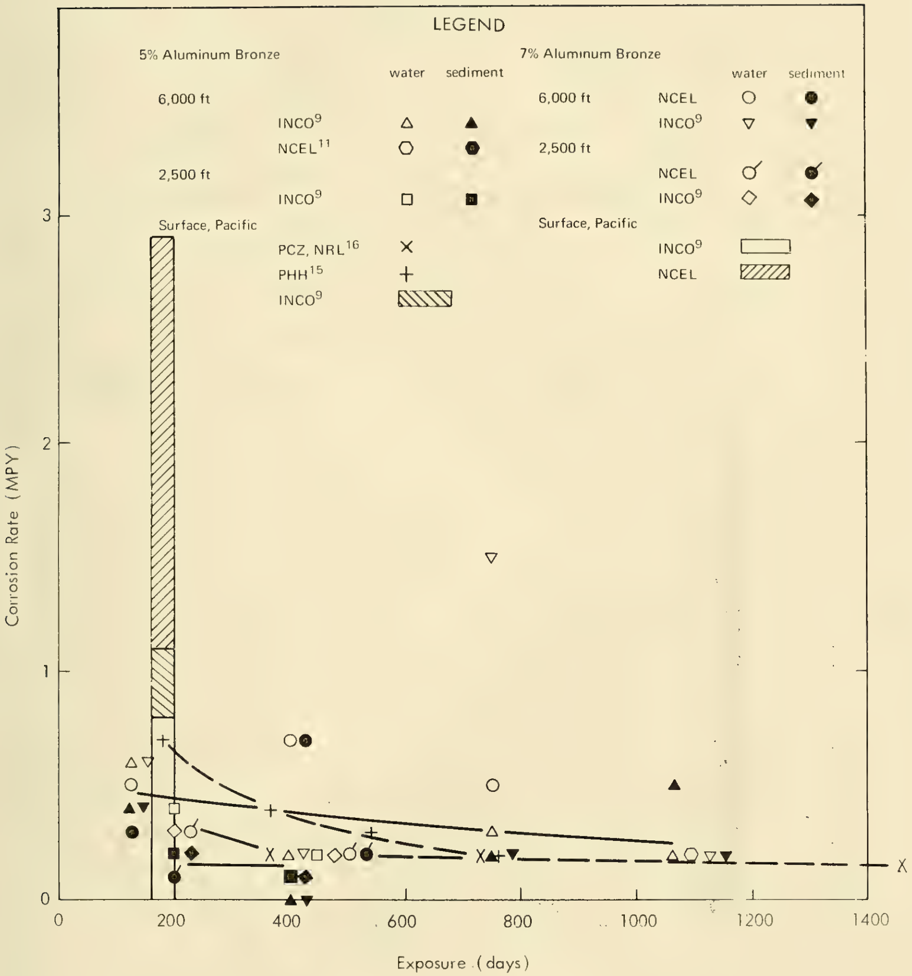

Figure 25. Corrosion rates of wrought aluminum bronzes.

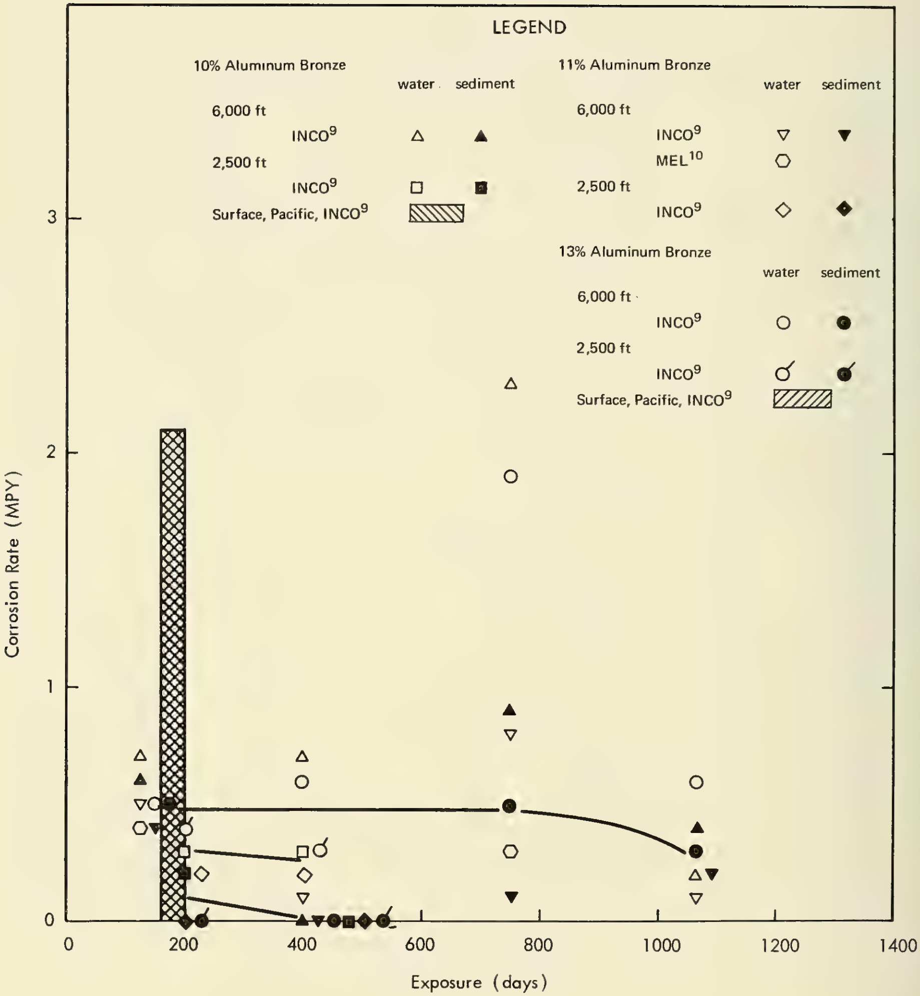

Figure 26. Corrosion rates of cast aluminum bronzes.

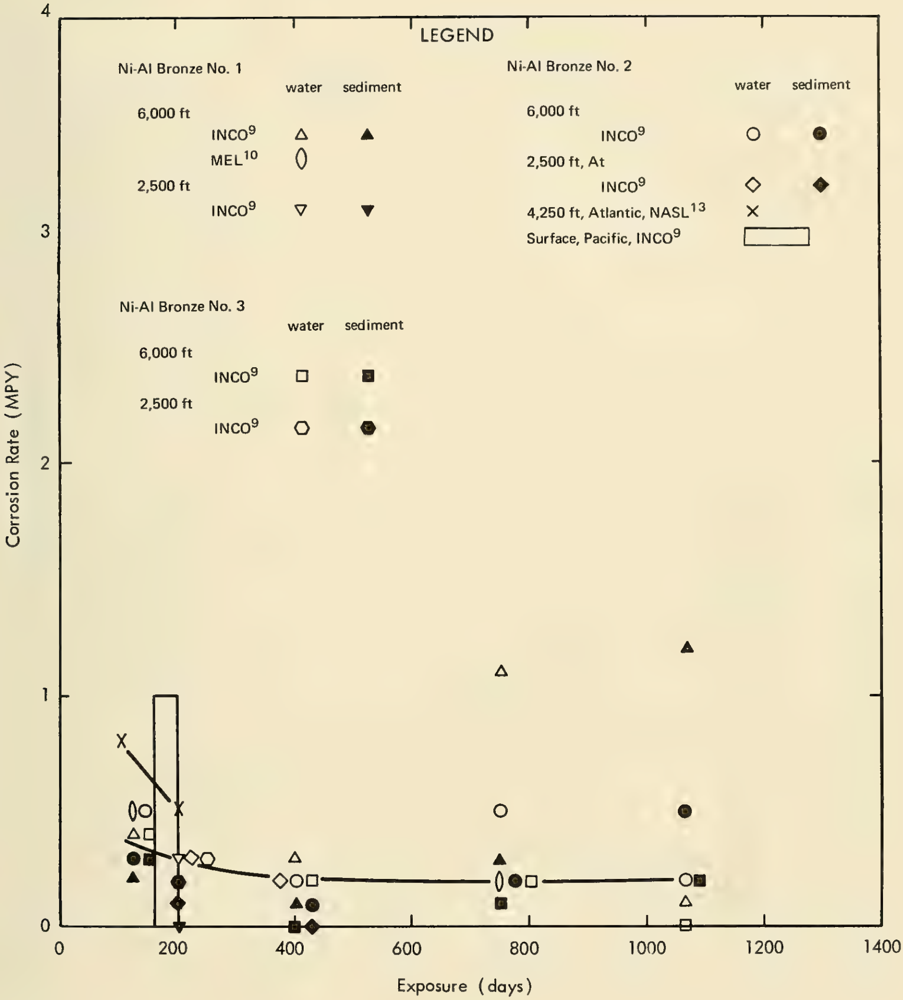

Figure 27. Corrosion rates of nickel – aluminum bronzes.

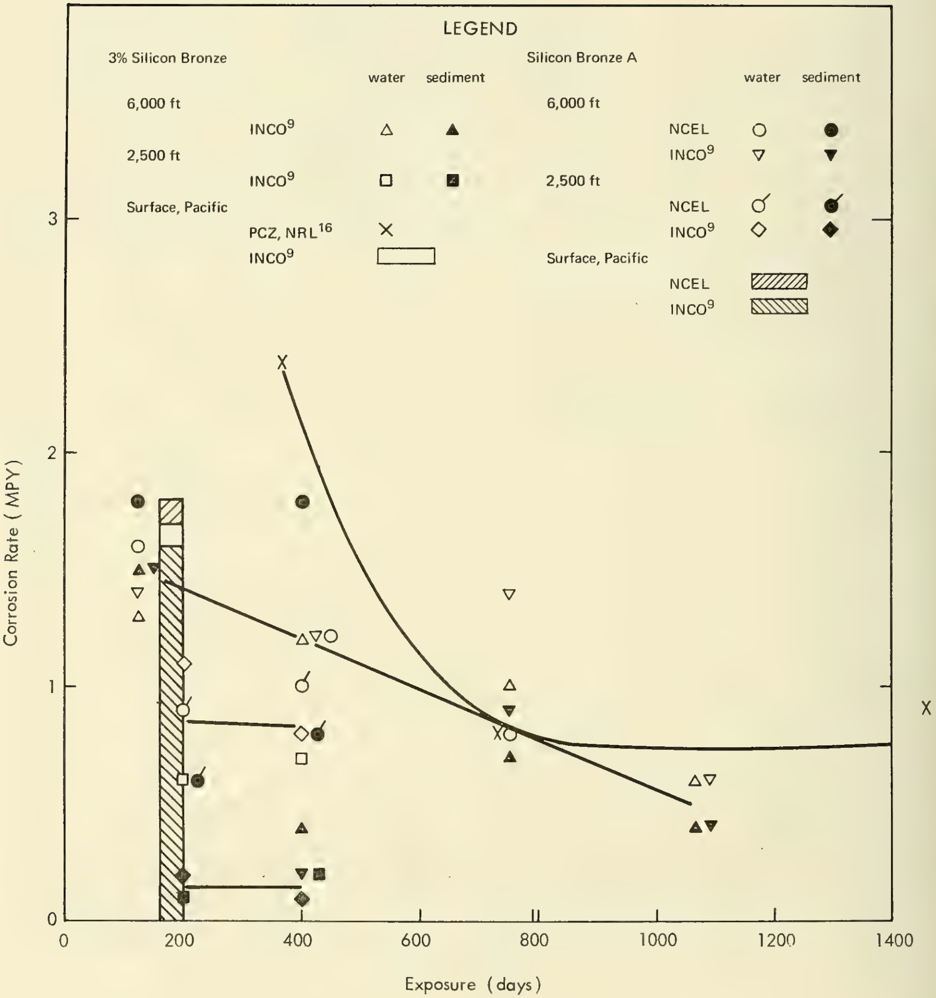

Figure 28. Corrosion rates of silicon bronzes.

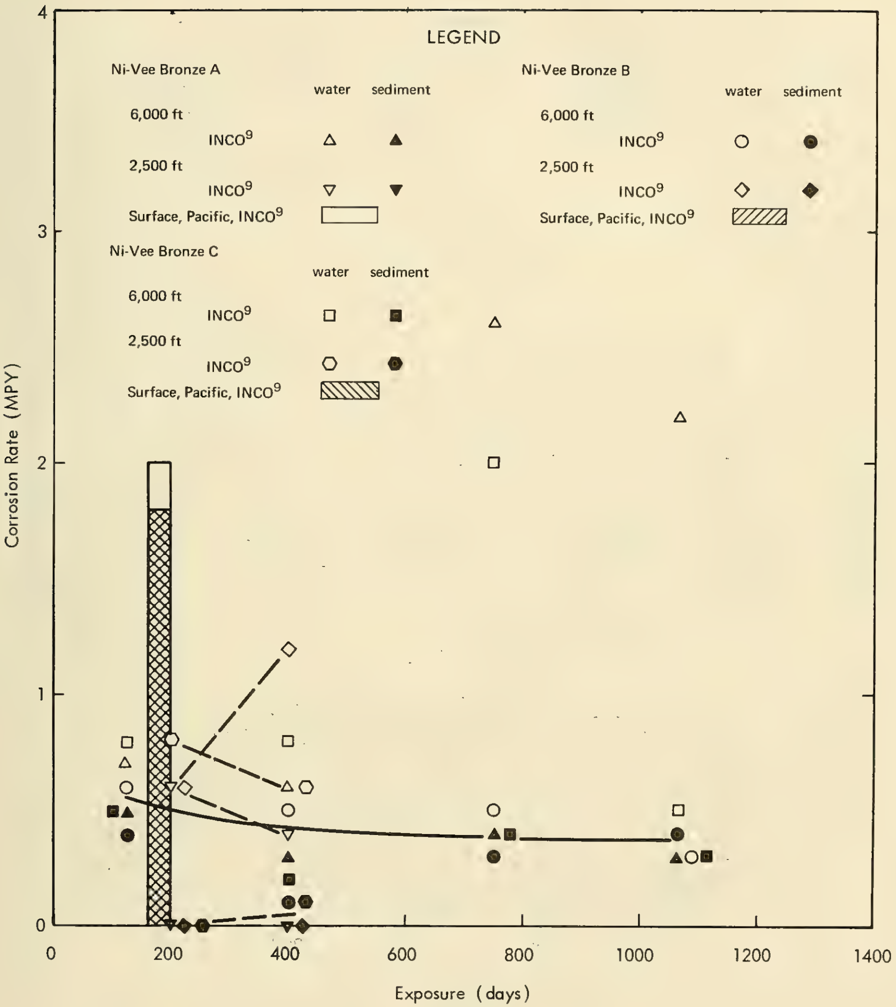

Figure 29. Corrosion rates of Ni - Vee bronzes.

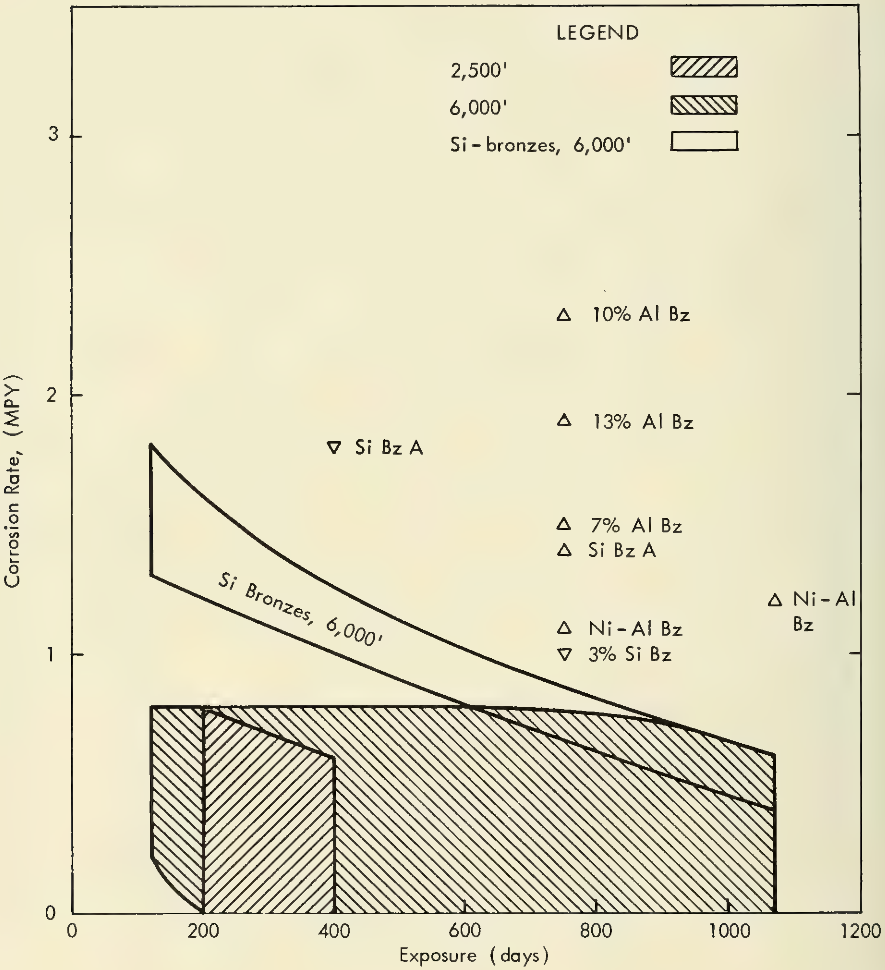

Figure 30. Corrosion rates of bronzes.

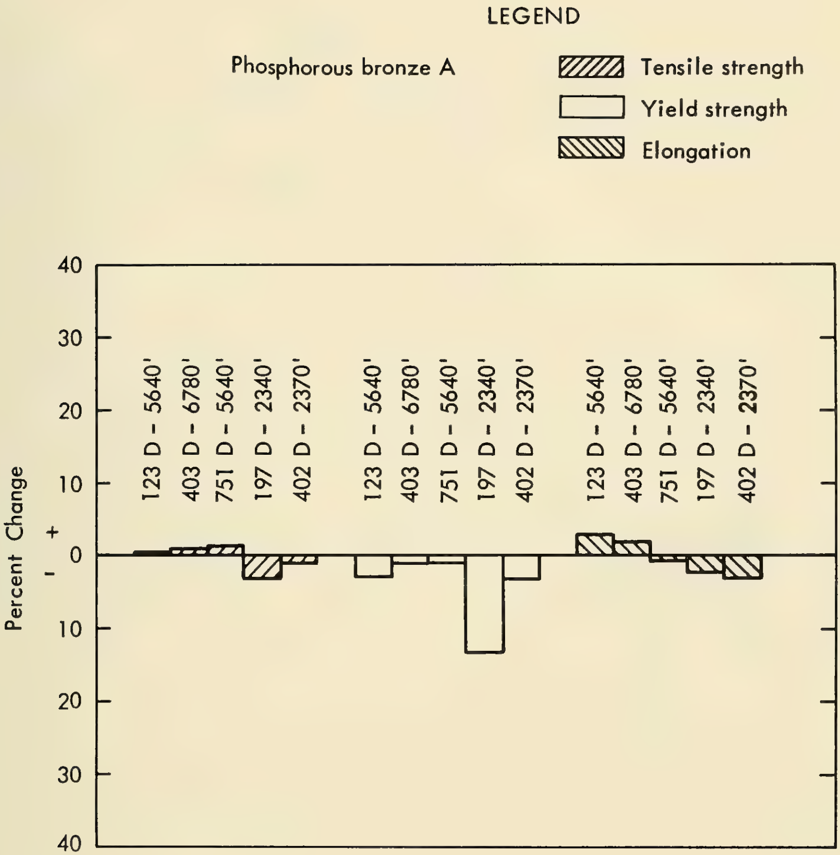

Figure 31. Effect of exposure on the mechanical properties of phosphorous bronze A.

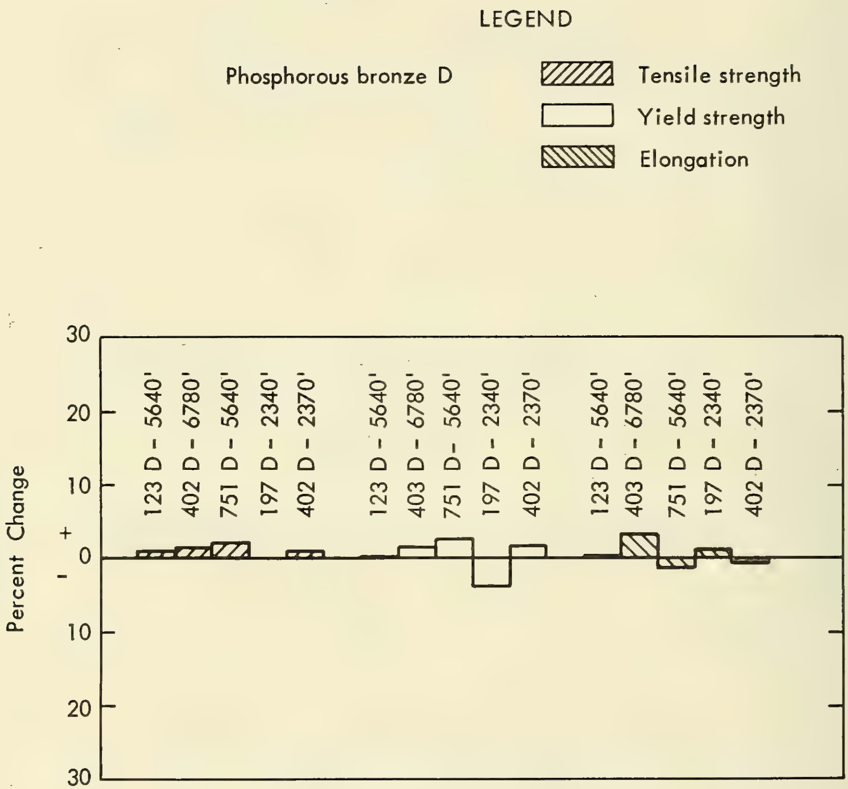

Figure 32. Effect of exposure on the mechanical properties of phosphorous bronze D.

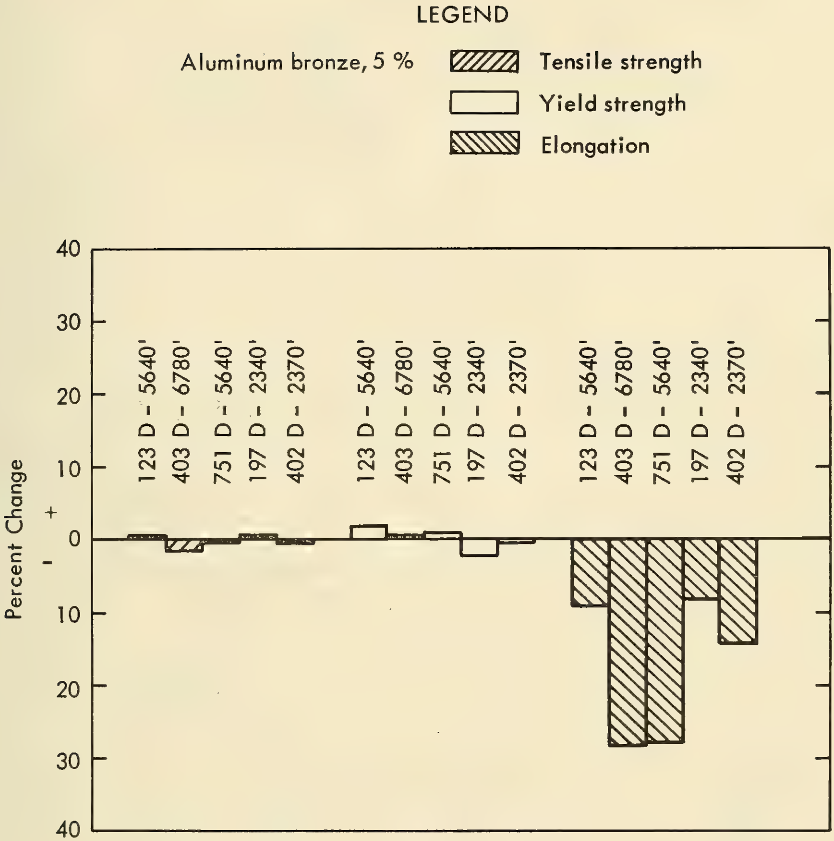

Figure 33. Effect of exposure on the mechanical properties of aluminum bronze, 5% aluminum.

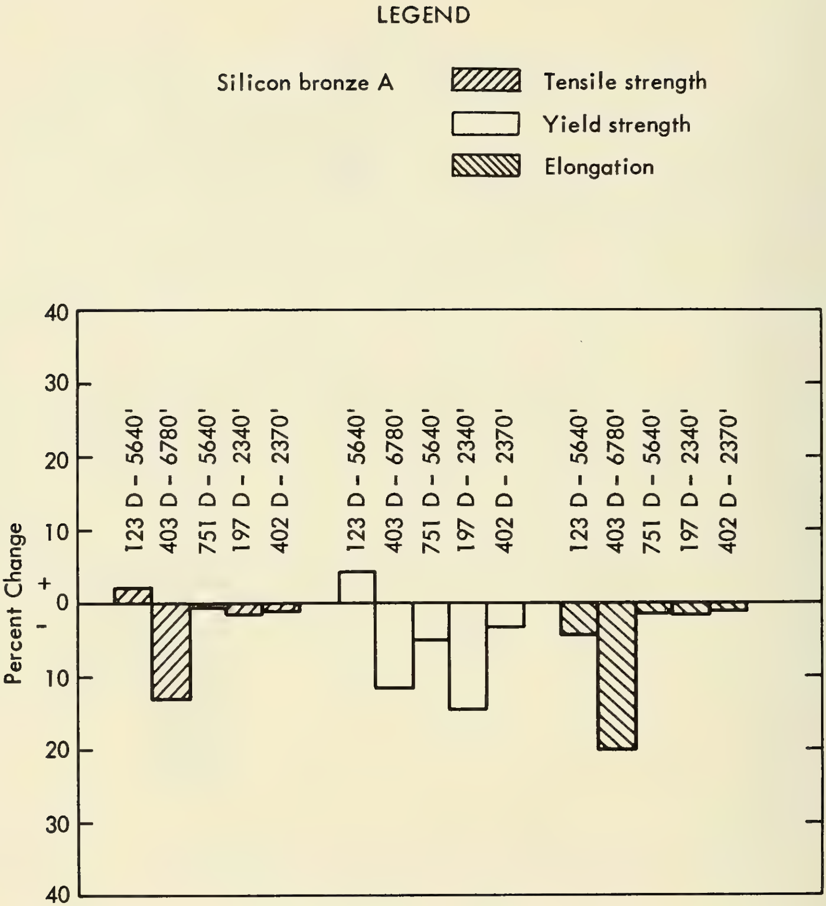

Figure 34. Effect of exposure on the mechanical properties of silicon bronze A.

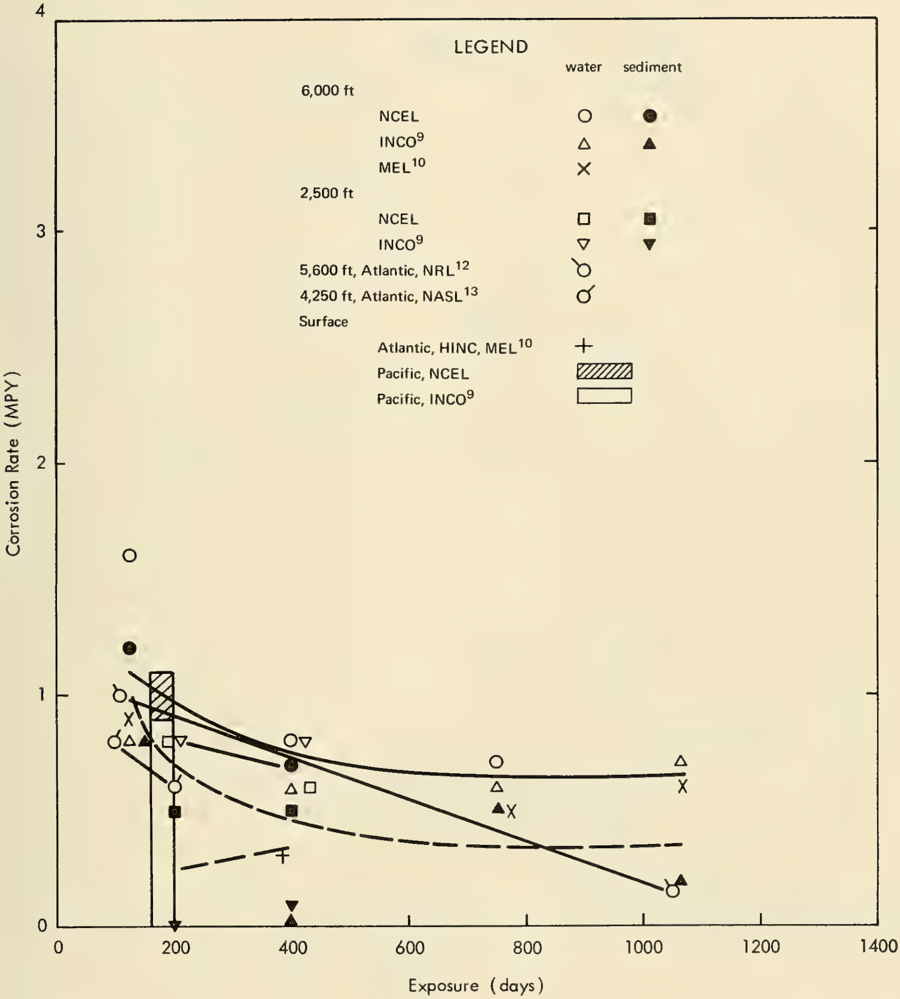

Figure 35. Corrosion rates of 90 – 10 copper – nickel alloy.

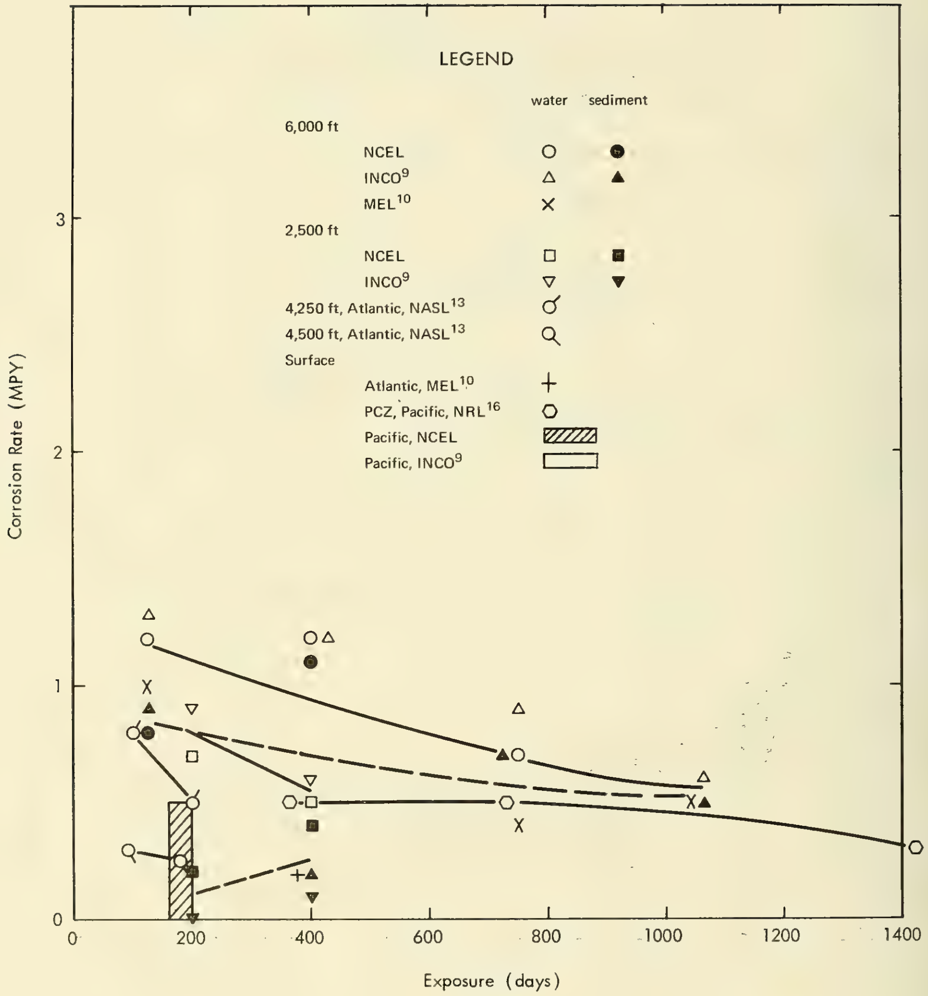

Figure 36. Corrosion rates of 70-30 copper-nickel alloy containing 0.5 % iron.

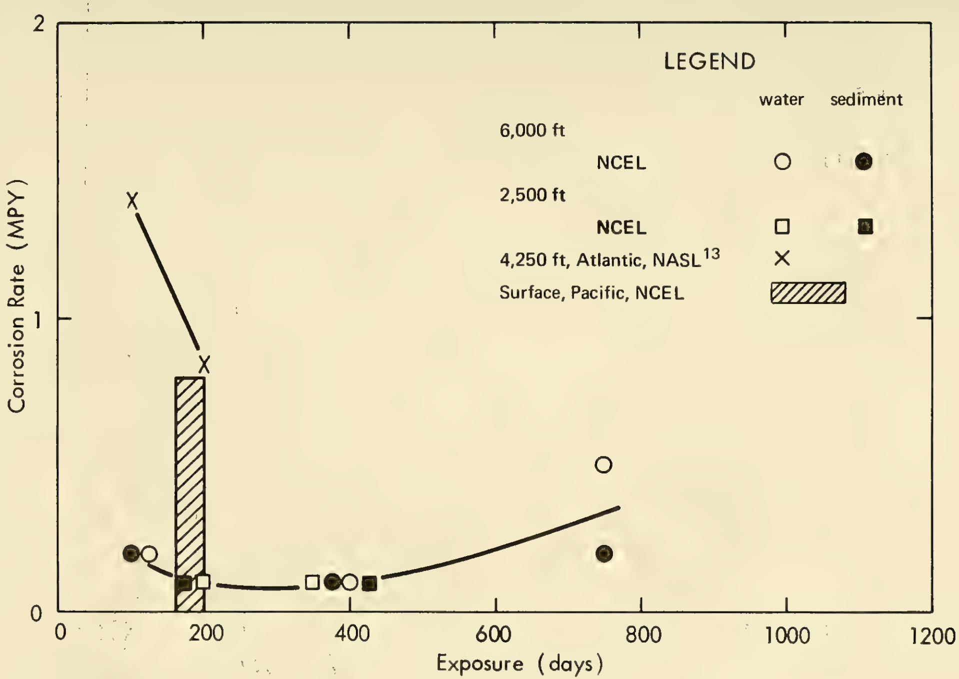

Figure 37. Corrosion rates of 70 - 30 copper - nickel alloy containing 5 percent iron.

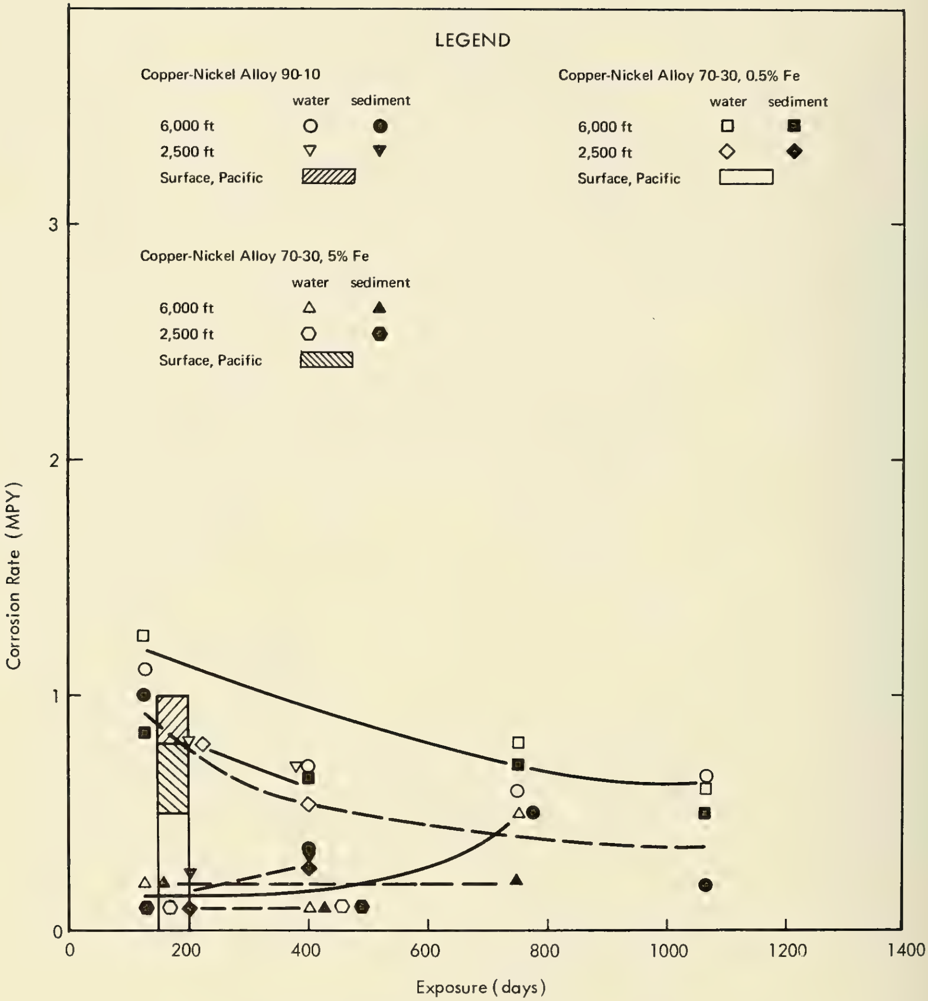

Figure 38. Corrosion rates of copper-nickel alloys.

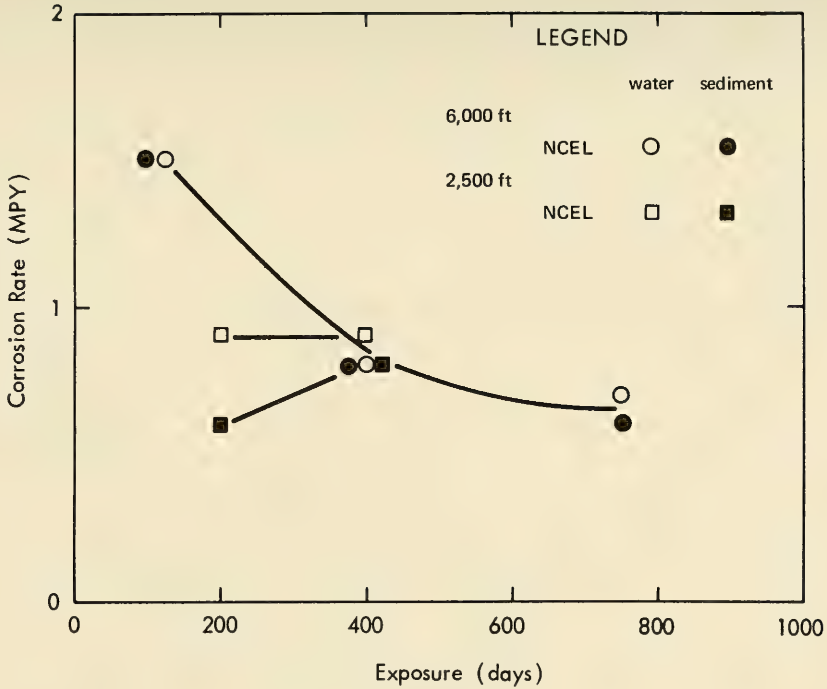

Figure 39. Corrosion rates of 95-5 copper-nickel alloy.

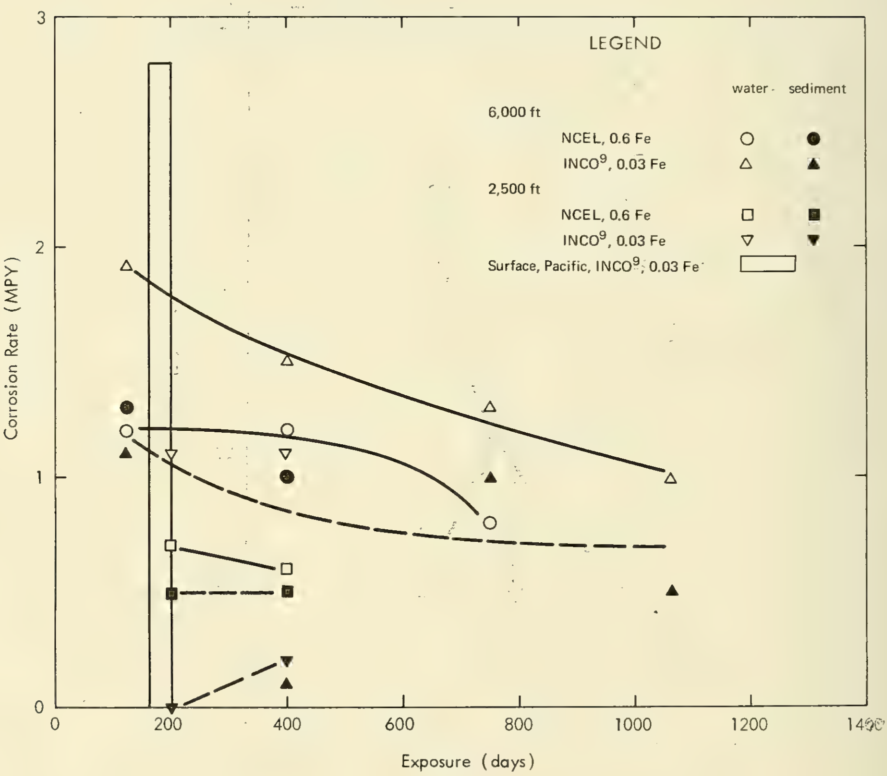

Figure 40. Corrosion rates of 80-20 copper-nickel alloy.

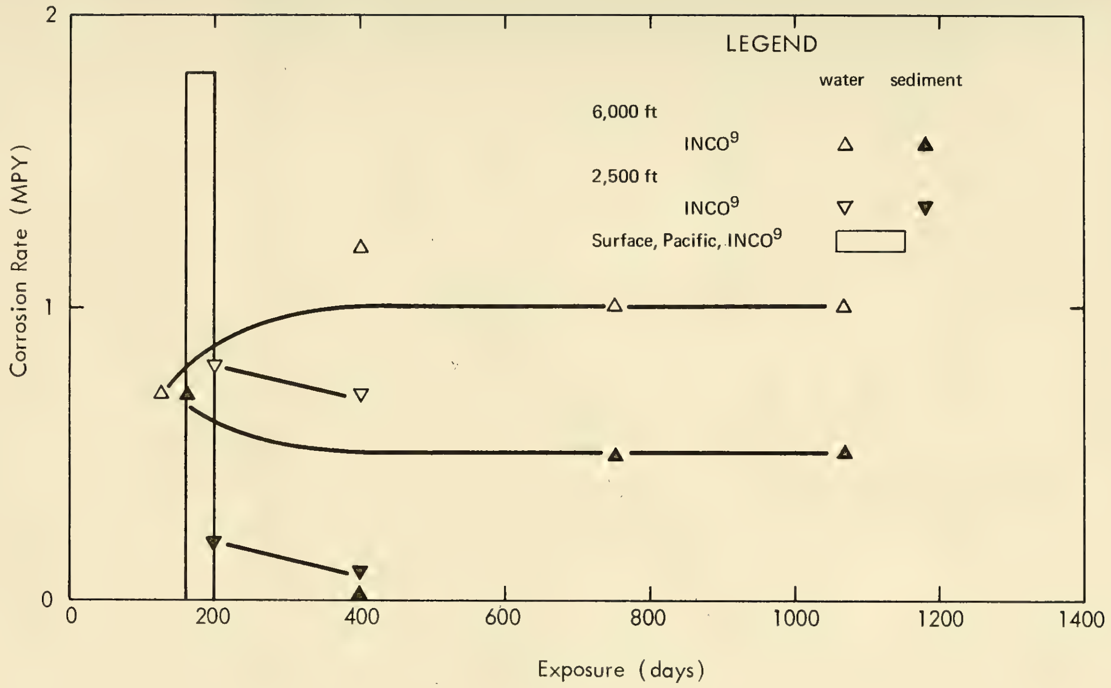

Figure 41. Corrosion rates of 55 - 45 copper-nickel alloy.

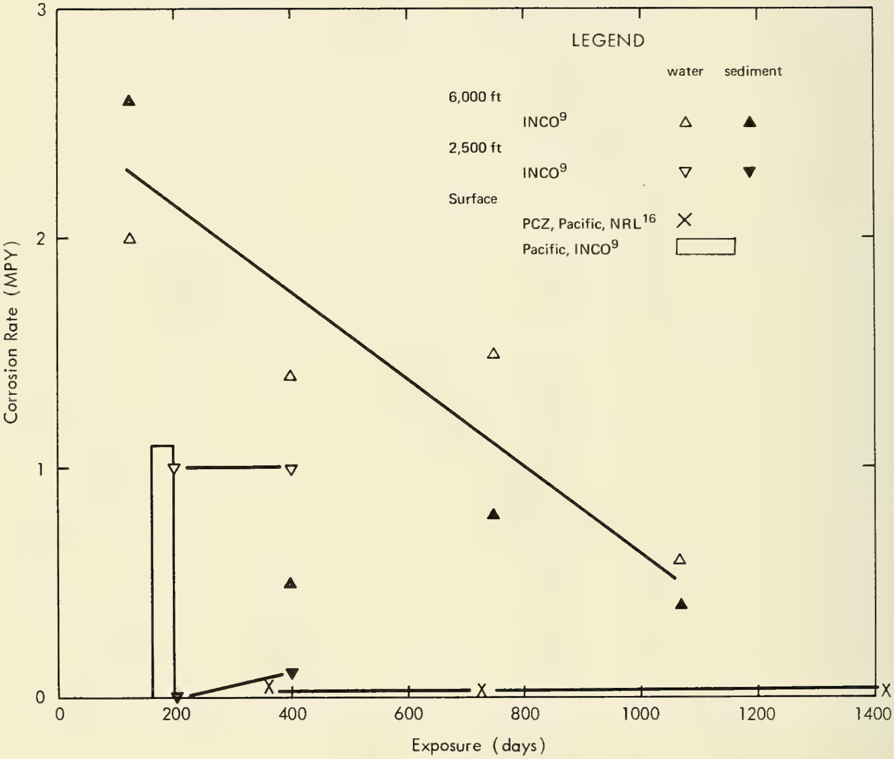

Figure 42. Corrosion rates of 65-18 nickel-silver alloy.

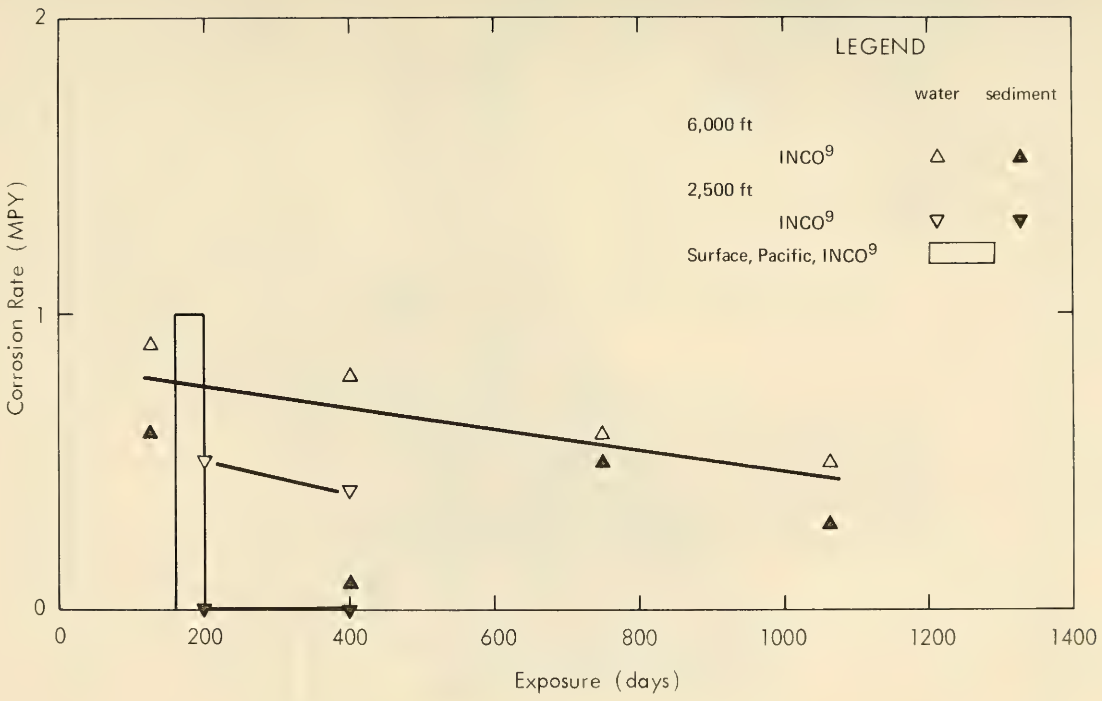

Figure 43. Corrosion rates of 62 Cu - 25 Ni - 8 Zn - 5 Pb alloy.

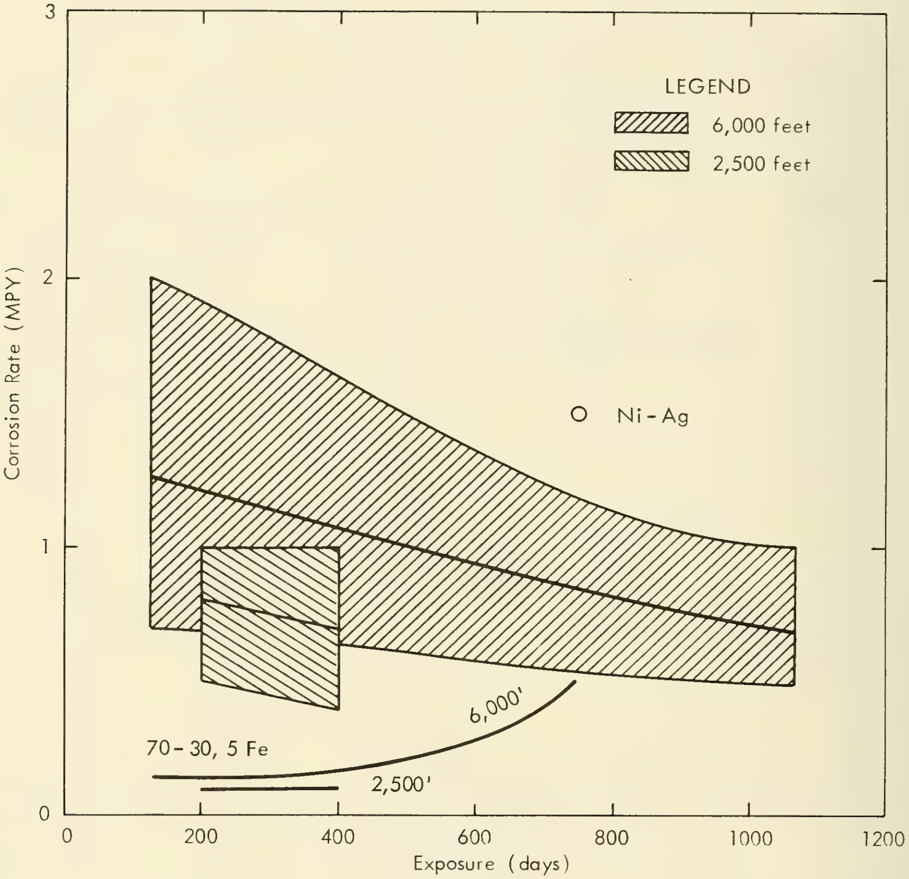

Figure 44. Corrosion rates of copper - nickel alloys in sea water.

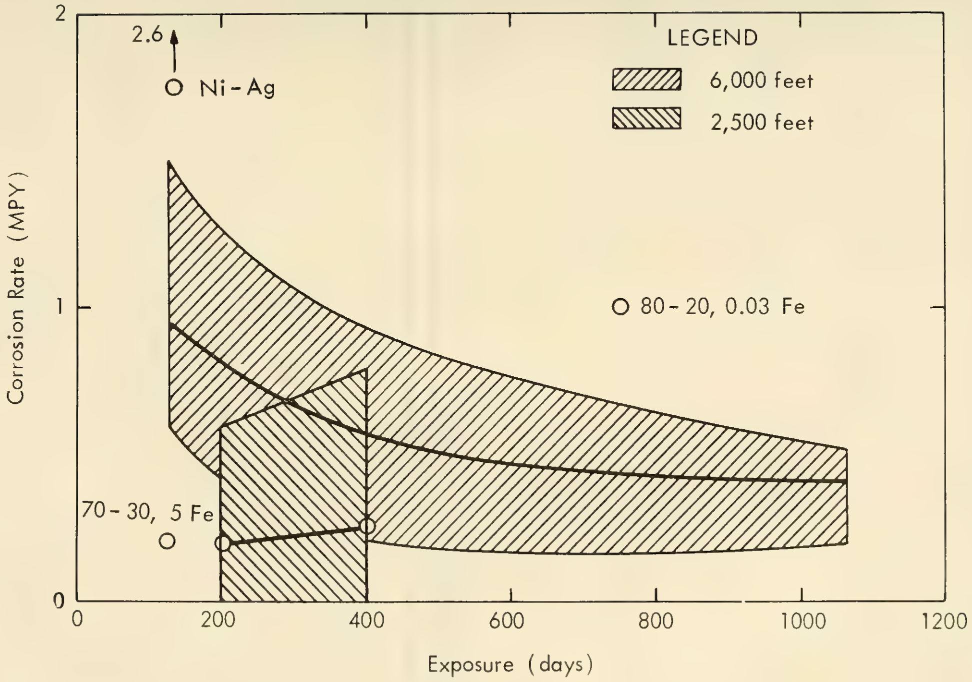

Figure 45. Corrosion rates of copper-nickel alloys in the bottom sediments.

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(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*
Naval Civil Engineering Laboratory
Port Hueneme, California

2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP

3. REPORT TITLE
CORROSION OF MATERIALS IN HYDROSPACE, PART IV - COPPER AND COPPER ALLOYS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

5. AUTHOR(S) *(First name, middle initial, last name)*
Fred M. Reinhart

6. REPORT DATE
April 1968

7a. TOTAL NO. OF PAGES
118

7b. NO. OF REFS
17

8a. CONTRACT OR GRANT NO.

b. PROJECT NO. Y-F015-21-05-001

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
TN-961

9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. DISTRIBUTION STATEMENT

CLEARED FOR UNLIMITED DISTRIBUTION

~~Each transmittal of this document outside the agencies of the U. S. Government must have prior approval of the Naval Civil Engineering Laboratory.~~

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY
Naval Facilities Engineering Command
Washington, D. C.

13. ABSTRACT

A total of 1050 specimens of 46 different copper alloys were exposed at two depths, 2,500 and 6,000 feet, in the Pacific Ocean for periods of time varying from 123 to 1064 days in order to determine the effects of deep ocean environments on their corrosion resistance.

Corrosion rates, types of corrosion, pit depths, stress corrosion cracking resistance, changes in mechanical properties and analyses of corrosion products of the alloys are presented.

Copper, beryllium-copper, arsenical admiralty brass, aluminum brass, nickel brass, G bronze, modified G bronze, M bronze, leaded tin bronze, phosphorous bronze A, phosphorous bronze D, nickel-aluminum bronzes, Ni-Vee bronze A, Ni-Vee bronze B, Ni-Vee bronze C, copper-nickel alloys 95-5, 80-20, 70-30 containing 0.5 percent iron, 70-30 containing 5 percent iron, 55-45, nickel-silver containing 18 percent nickel, and Cu-Ni-Zn-Pb corroded uniformly and their corrosion rates were low, 1 MPY or less after 1 year at a depth of 2,500 feet and after 2 years at a depth of 6,000 feet.

The remainder of the alloys were attacked by selective corrosion: commercial bronze, red brass, yellow brass, Muntz metal, Naval brass, manganese bronze, nickel-manganese bronze, wrought 5 and 7 percent aluminum bronzes, cast 10, 11 and 13 percent aluminum bronzes, 3 percent silicon bronze and silicon bronze A.

The copper alloys were not susceptible to stress corrosion cracking.

Only the mechanical properties of the alloys attacked by selective corrosion were adversely affected.

Unclassified

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Corrosion						
Materials						
Hydrospace						
Copper						
Copper alloys						
Ocean environment						
Corrosion resistance						

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(PAGE 2)

Unclassified

Security Classification

Abstract (cont'd)

The corrosion products consisted of cupric chloride, copper hydroxide-chloride, metallic copper, copper oxy-chloride and nickel hydroxide.